AR-010-124

DSTO-TR-0472

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A MARKOV MODEL FOR HF CHANNEL AVAILABILITY IN CENTRAL AUSTRALIA

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ABSTRACT

HF channel availability is an important consideration in the design and operation of HF radar and communications networks. Models for spectral occupancy or congestion as a function of time, geographic location and solar activity have been developed in recent years by several researchers, based on limited data sets recorded at several northern hemisphere locations. In this report, the extensive database of HF spectral surveillance and background noise measurements, recorded at Alice Springs in Central Australia as part of the Jindalee over-the-horizon radar project, is used to develop a model for HF channel availability. Parameters in a two-dimensional cyclostationary Markov model are estimated for representative months of Jindalee data. The resulting model may be used for short-term forecasting of HF channel availability for radar and communications, and as the starting point for a study into long-term trends in spectral usage.

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Electronics and Surveillance Research Laboratory
PO Box 1500
Salisbury, South Australia, Australia 5108

Telephone: (08) 8259 5555
Facsimile: (08) 8259 6567

AR No. AR–010–124

March, 1997

APPROVED FOR PUBLIC RELEASE

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EXECUTIVE SUMMARY

Models for HF channel availability derived from spectral occupancy measurements have been the subject of increasing attention during the past two decades. Such models find application in short-term forecasting of channel availability for HF radar and communications operations, and for long-term prediction of HF spectrum usage for spectrum management and evaluation. To date, most models have been developed using limited data sets recorded in northern hemisphere locations.

A two-dimensional cyclostationary Markov model for HF channel availability is developed here, which accounts for diurnal variations in spectral usage and propagation conditions. Three parameters describe the model, namely the probability that a given channel in a selected band is available, the conditional probability that a channel is available in a selected hour given that it was available in the previous sample time, and the conditional probability that a selected channel is available given the availability of an adjacent channel. This model is the simplest one which permits predictions of available channel bandwidth and lifetime.

The extensive Jindalee spectral surveillance database, recorded at Alice Springs in central Australia in support of over-the-horizon radar operations, was used to obtain relative frequency estimates for the model parameters for five representative months in the last decade. Three months (June 1986, January 1991, September 1993) were chosen to span the seasonal and solar cycle variation in propagation conditions, while two additional months (June 1985 and June 1995) were chosen as months with similar propagation conditions to assess long-term trends in spectral usage. Modelling results are graphically presented and described, and a brief discussion of model testing and possible extensions given.

The results of this research have been successfully used as an input in the simulation and modelling for the ADF HF modernisation network (Project JP2043). It also represents the most modern approach to spectrum occupancy analysis which can be used in the other geographical areas of Australia and elsewhere. Possible Defence applications of the developed model include efficient management of the Jindalee over-the-horizon radar, assessment of the long-term HF spectral usage in Central Australia and forecasting of the HF spectral needs of the ADF.

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1 Introduction and Review

Spectral occupancy measurements and subsequent data modelling have been the subject of increasing attention since the early 1980's. With the congested nature of the HF spectrum, where users with differing requirements compete for diminishing available bandwidth within the International Telecommunications Union (ITU) frequency allocations, there is strong motivation for developing models for spectrum usage. Such models find application in both short-term forecasting of channel availability for HF radar and communications applications, and for long-term prediction of HF spectrum usage for spectrum management and evaluation.

Allocation congestion models seek to describe the fraction of each ITU user allocation which is occupied by users, as a function of time and geographic location. The congestion Q_k is defined as the fraction of measurement channels within the kth user allocation for which the observed power exceeds a prescribed threshold [6, 18, 24]. These models are motivated by the desire for broad scale and long-term knowledge of the HF propagation conditions for HF communications network analysis and planning, incorporating both environmental factors and evolving patterns of spectrum usage. Such congestion models may be combined with HF skywave prediction programs to examine effects of interference and shortwave fadeouts on communications reliability [20]. Spectral occupancy is important for for HF frequency planning [27], for HF DSP based management systems [23], and in over-the-horizon radar applications [7, 8].

Pantjiaros *et al.* [22] have reviewed the HF spectral occupancy measurements in Europe since 1982, and given examples of models for the allocation congestion [22]. One model is the Laycock-Gott logit model [15, 18]

$$Q_k = \frac{e^{y_k}}{1+e^{y_k}}, \tag{1}$$

where the index y_k is a complicated empirical function of geographic location, time of day, time of year and sunspot number. The Laycock-Gott model requires 25 parameters to be determined by fitting the model to measured data in all allocations, together with 95 additional parameters corresponding to each of the 95 ITU user allocations. The congestion dependence on measurement bandwidth has also been investigated by Chan *et al.* [4] and Gott *et al.* [14], using a related logit model. Measurements at two European locations have suggested that this bandwidth dependence is time invariant and location independent [3, 21].

Another approach to spectral occupancy modelling is to describe the complementary channel availability statistics. Of interest here is not simply ITU allocation congestion, but the pattern of channel availability within ITU allocations, for a given bandwidth and duration. The emphasis is on providing an individual HF spectral user with tools for efficiently exploiting available channels. Time modelling of HF interferences using channel availability statistics was performed by Goutelard and Caratori [16]. Spaulding and Hagn [24] first suggested the use of the first-order Markov chains for modelling a single channel availability. Using a statistical approach to Bernoulli trials with Markov dependence from [17], Gibson [9], and Gibson and Arnett [11, 12] extended the work of

[24] to a two-dimensional first-order Markov chain model which accounts for intra-channel correlation. Other possible approaches to the modelling of various radiocommunications phenomena which appear as multidimensional stochastic processes are reported in [10]. The theory and important applications of multidimensional Markov models are described in [1, 2, 5, 19, 25, 26, 28].

In this report, an extension of the channel availability model of [9] and [11, 12] is detailed, which accounts for diurnal variations in spectral usage and propagation conditions. Channel availability within statistically similar frequency bands in a given season and solar cycle epoch is modelled as a cyclostationary two-dimensional first-order Markov chain. Three Markov parameters are required in the model, with each parameter expressed as a function of time of day. The three parameters correspond with the unconditional probability that the channel is available, the conditional probability that the channel is available given that it was available at the previous time step, and the the conditional probability that the channel is available given that an adjacent channel is available. This three parameter model is the simplest model which permits predictions of available channel bandwidth and lifetime for HF spectral usage.

Model parameters may be estimated from spectral surveillance data using relative frequency estimates. The extensive Jindalee spectral surveillance database [7, 8] recorded at Alice Springs in Central Australia is used here to estimate the channel availability model parameters for representative months of data. Three specific months of data were chosen to span seasonal and solar cycle variation, namely June 1986 for winter in a low solar activity year, January 1991 for summer in a high solar activity year, and September 1993 for a mid-season, mid - solar cycle month. Two additional months (June 1985 and June 1995) were chosen for modelling to assess long term trends in spectral usage, both being winter months with similar solar activity conditions.

In Section 2, the formalism for the two-dimensional Markov model for channel availability is introduced, which is an extension of the model developed by Gibson and Arnett [11, 12] to incorporate diurnal cyclostationary. In Section 3, the Jindalee spectral surveillance and background noise databases used to estimate model parameters for Central Australia are described. An important inconsistency between the two databases uncovered during this work is outlined. The results of modelling the five chosen months of Jindalee data are described in Section 4. A summary of the contribution of this work is given in Section 5, with a brief discussion of possible future model testing and extensions. Detailed derivation of all two-dimensional transition probabilities is given in the Appendix A.

2 Channel Availability Model

We develop here a two-dimensional first-order Markov model for channel availability recorded in the Jindalee data, following the work of Gibson and Arnett [11, 12]. Cyclostationarity is incorporated into the model, where model parameters vary as functions of time of day to capture the diurnal variation in spectral usage manifest in spectral surveillance data.

Let $s_j(\tau_i)$ be the spectral surveillance power (in dB/Hz) measured at time τ_i in frequency channel j. If $b_j(\tau_i)$ is the measured background noise level in the jth channel, then a binary *channel availability* function $x_j(\tau_j)$ may be defined by

$$x_j(\tau_i) = \begin{cases} 1 & \text{if } s_j(\tau_i) - b_j(\tau_i) \leq T \\ 0 & \text{if } s_j(\tau_i) - b_j(\tau_i) > T \end{cases}, \tag{2}$$

where T is a prescribed threshold value. That is, frequency channel j is *available* ($x_j = 1$) if the measured spectral power is less than T above the background noise level, and *occupied* ($x_j = 0$) otherwise.

Recorded spectral surveillance data may be used to estimate parameters in a channel availability model. Given the observed diurnal variation in surveillance data, it is convenient to express the sample times τ_i in the form

$$\tau_i(d, h, t_i) = (d-1)T_d + hT_h + t_i, \tag{3}$$

where $d = 1, 2, \ldots, D$ indexes the D days of duration T_d, $h = 0, 1, \ldots, 23$ denotes each hour of duration $T_h = T_d/24$ within each day, and where $0 \leq t_i < T_h$ denotes the sample time within each hour. Here, $i = 0, 1, \ldots, N(d,h)$ indexes the $N(d,h)$ samples on day d in hour h. The channel availability function for the jth channel on day d, hour h and at sample time t_i may then be written as

$$x_j(d, h, t_i) = x_j(\tau_i(d, h, t_i)). \tag{4}$$

Following Gibson and Arnett [11], a first-order two-dimensional Markov chain model for channel availability is developed here. The observation that spectral usage follows a strong diurnal cycle suggests that the channel availability may be modelled as a cyclostationary process with a period of one day; model parameters for a given season and solar cycle epoch may then be estimated from surveillance measurement data. In the first instance, no attempt is made to explicitly model seasonal or solar cycle variations, although it may be possible to at least model seasonal periodicity within a polycyclostationary model for sufficiently long measurement data series. Geographic variations in channel availability are also neglected here, with only single site surveillance data available.

Instead of attempting the computationally prohibitive task of modelling each measured frequency channel separately, N_c adjacent channels which appear *statistically similar* may be collectively modelled. These N_c channels may correspond to a particular ITU frequency allocation, but more generally they will be some smaller slice of the spectrum within a given allocation.

Three Markov parameters are used to describe channel availability in each band of N_c consecutive statistically similar frequency channels. We define the probability

$$p(h) = \Pr[x_j(d, h', t_i) = 1 | h' = h] \tag{5}$$

that a given channel in the selected band is available in hour h, the conditional transition probability

$$\lambda(h) = \Pr[x_j(d, h', t_i) = 1 | x_j(d, h', t_{i-1}) = 1, h' = h] \tag{6}$$

that a channel is available during hour h, given that it was available at the previous sample time in the same hour, and the intra-channel conditional probability

$$\mu(h) = \Pr[x_j(d,h',t_i) = 1 | x_{j-1}(d,h',t_i) = 1, h' = h] \tag{7}$$

that a channel is available in hour h, given that the adjacent frequency channel is available.

Introducing the notation

$$N(h) = \sum_{d=1}^{D} N(d,h) \tag{8}$$

for the total number of data samples in hour h for all D days sampled, relative frequency estimates for the model parameters $p(h)$, $\lambda(h)$, and $\mu(h)$ are respectively given by

$$\widehat{p}(h) = \frac{S(h)}{N_c\, N(h)} \ , \tag{9}$$

$$\widehat{\lambda}(h) = \frac{N(h)\, r_\lambda(h)}{(N(h)-D)\, S(h)} \ , \tag{10}$$

and

$$\widehat{\mu}(h) = \frac{N_c\, r_\mu(h)}{(N_c - 1)\, S(h)} \ , \tag{11}$$

where

$$S(h) = \sum_{j=1}^{N_c} \sum_{d=1}^{D} \sum_{i=1}^{N(d,h)} x_j(d,h,t_i) \ , \tag{12}$$

$$r_\lambda(h) = \sum_{j=1}^{N_c} \sum_{d=1}^{D} \sum_{i=2}^{N(d,h)} x_j(d,h,t_{i-1})\, x_j(d,h,t_i) \ , \tag{13}$$

and

$$r_\mu(h) = \sum_{d=1}^{D} \sum_{i=1}^{N(d,h)} \sum_{j=2}^{N_c} x_{j-1}(d,h,t_i)\, x_j(d,h,t_i). \tag{14}$$

Gibson and Arnett [11, 12] introduced eight transition probabilities to describe a two-dimensional Markov model for channel availability. Extending their definition to incorporate diurnal cyclostationarity, we define the eight transition probabilities as

$$\Phi_{klm}(h) = \Pr[x_j(d,h',t_i) = k | x_{j-1}(d,h',t_i) = l, x_j(d,h',t_{i-1}) = m, h' = h], k, l, m = 0, 1. \tag{15}$$

That is, Φ_{klm} denotes the probability that the jth channel at time t_i is in state k, given that the jth channel at the previous time t_{j-1} is in state l and that the $(j-1)$th channel at time t_i is in state m. In particular, the conditional probability that a channel is available in hour h, given that it was available at the previous time step and that the adjacent channel at the same time step is available, is given by

$$\Lambda(h) = \Phi_{111}(h) = \Pr[x_j(d,h',t_i) = 1 | x_{j-1}(d,h',t_i) = 1, x_j(d,h',t_{i-1}) = 1, h' = h]. \tag{16}$$

The introduction of $\Lambda(h)$ is sufficient for the expression of the other seven transition probabilities in terms of $\Lambda(h)$, $p(h)$, $\lambda(h)$ and $\mu(h)$, as outlined in Appendix A. However, it may be shown that [9],

$$\Lambda^{(1)}(h) = \lambda(h) + (1 - \lambda(h))\rho(h), \tag{17}$$

where $\Lambda^{(1)}$ denotes the first order approximation of Λ, and where

$$\rho(h) = \frac{\mu(h) - p(h)}{1 - p(h)} \tag{18}$$

is the intra-channel correlation coefficient defined by Laycock *et al.* [18]. By virtue of (17) and (18), the two dimensional Markov model can be described to first order in terms of only three independent parameters, namely $p(h)$, $\lambda(h)$ and $\mu(h)$.

As a check on the validity of the first order approximation, $\Lambda(h)$ may be estimated directly from the data using

$$\widehat{\Lambda}(h) = \frac{u(h)}{v(h)}, \tag{19}$$

with

$$u(h) = \sum_{j=2}^{N_c} \sum_{d=1}^{D} \sum_{i=2}^{N(d,h)} x_j(d,h,t_{i-1})\; x_{j-1}(d,h,t_i)\; x_j(d,h,t_i) \tag{20}$$

and

$$v(h) = \sum_{j=2}^{N_c} \sum_{d=1}^{D} \sum_{i=2}^{N(d,h)} x_j(d,h,t_{i-1})\; x_{j-1}(d,h,t_i). \tag{21}$$

3 Jindalee Spectral Surveillance and Background Noise Data

Spectral surveillance and background noise data have been recorded for much of the last decade as part of the real-time Frequency Management System (FMS) for the Jindalee over-the-horizon radar project at Alice Springs in Central Australia. An overview of the Jindalee FMS is given by Earl and Ward [7, 8]. The HF spectral surveillance subsystem of interest here is used to select unoccupied frequency channels for radar operations, and to estimate the background noise level so that a radar operating frequency may be chosen which maximises the clutter to noise ratio in the required radar coverage direction.

The Jindalee spectral surveillance data consists of power measurements received at Alice Springs by an omnidirectional whip antenna for successive 2 kHz frequency channels in the range 5-45 MHz. The nominal sampling interval is 12 minutes, although gaps in data collection on timescales of minutes to days are introduced by equipment faults, system development downtime and competing experiments. The power recorded for each 2 kHz channel is the result of summing and averaging multiple power measurements to reduce data variance and the effect of impulsive noise. Specifically, a receiver with 20 kHz bandwidth is stepped across the HF spectrum, with time series data collected for 5 ms

at each step, with a sampling rate of 51.2 kHz. Spectral analysis using the FFT gives a fundamental frequency resolution of 200 Hz; ten adjacent 200 Hz spectral estimates are summed to give the 2 kHz resolution estimate. Ten similar scans are recorded, with those scans subject to impulsive noise identified and eliminated. The final power estimate is then an average of the remaining 2 kHz resolution power estimates. Thus, up to 100 power spectral estimates are summed and averaged to obtain the recorded power for each 2 kHz frequency channel. The data is calibrated with reference to injected noise at a known level of -170 dBW/Hz.

Typical spectral surveillance data is displayed in Figure 1, where one day of data (Day 244, September 1993) recorded between 5 and 30 MHz is shown as an intensity spectrogram. Power is shown with an intensity colour scale in units of dBW/2kHz. Time is measured in Universal Time (UT), with 0 UT corresponding to 0930 Central Australian local time. Although the pixel resolution is insufficient to show individual 2 kHz frequency channels, large scale features in spectral usage can be identified. Strong international broadcast bands are evident (e.g., near 7.5 MHz, 9.8 MHz, 12 Mhz, 15.3 MHz and 17.8 MHz) against the diurnal drift of spectral usage to low frequencies at night time. Increased signal strength is also evident at night time, which results from reduced ionospheric absorption. The CB channels around 27 MHz are a noteworthy daytime feature at the high frequency end of the spectrum. Although spectral surveillance data is recorded up to 45 MHz by the Jindalee system, most data above 30 Mhz is galactic background noise, and is of little interest for channel availability modelling.

In Figure 2, spectral surveillance data collected on two successive days (Days 244-245 in September 1993) in the frequency range 11-12 MHz is shown with sufficient resolution to see the individual 2 kHz sampled channels. This segment of data spans three different ITU allocations, namely Aeronautical Mobile (11.175 - 11.400 MHz), Fixed (11.400 - 11.650 MHz) and Broadcast (11.650 - 12.050 MHz) bands. The remarkable feature of this data is the strong and reproducable diurnal variation in the recorded power measurements, a pattern which is repeated throughout the entire HF spectrum and throughout a given month of data. This pattern arises from the diurnal variation in propagation conditions, together with the programmed and habitual use of the HF spectrum by individual users. Within a given month, the spectral surveillance data for each day may be treated in the first instance as a sample realisation of the diurnal cyclostationary model outlined in Section 2.

In Figure 3, the time interval between successive Jindalee surveillance sweeps is plotted as a function of timestamp number for a typical data set. Although the sampling interval is irregular, with occasional data gaps and other times of anomalously short sampling interval, most samples are recorded approximately every 12 minutes, giving 5 samples each hour. To simplify the data modelling, regular sampling was assumed, so that typically $N(d,h) = 5$ on day d in hour h in the model parameter estimation. Data series with significant irregular gaps were neglected in the parameter estimation.

Background noise measurements are more problematic, given the congested nature of the HF spectrum. Jindalee noise measurements are recorded using both the omnidirectional antenna, and a range of directional antennas covering the Jindalee over-the-horizon radar surveillance region. Only the omnidirection measurements are considered here. One

background noise measurement is recorded for each 1 MHz channel in the range 5-45 MHz, by examining the quietest 26 kHz channel (allowing for skirt selectivity in the 20 kHz receiver passband) in each 1 MHz segment. As with the spectral surveillance data, ten data scans are initially recorded, each consisting of 100 power spectral estimates for the chosen 20 Khz band, with a 200 Hz resolution. Measurements affected by noise or radio frequency interference (RFI) are removed, and the remaining data averaged to give the background noise measurement. Since background noise is only a slowly varying function of frequency, the 1 MHz frequency resolution in the final estimate is quite adequate. Background noise below about 20 MHz is primarily of atmospheric origin, and varies on diurnal, seasonal and solar cycle timescales with the ionospheric state. Noise above 20 MHz is predominantly galactic radio noise, with little day-to-day average variation manifest.

An unexpected inconsistency between the Jindalee spectral surveillance data and the background noise data collected on the omnidirectional whip antenna was discovered in the course of this investigation. Specifically, the measured background noise is biased by spectral usage. This appears to be due to a flawed implementation of the background noise filtering algorithm described above. This inconsistency is illustrated in Figure 4, where the five hundred 2 kHz spectral surveillance channels recorded in the range 5-6 MHz are plotted as a function of time. The superposition of these five hundred plots appears as a solid black region in the figure. Excluding outlier data points, the low power envelope of this region traces the background noise level, being the locus of points from the set of spectral surveillance channels with minimum recorded power. The ominidirectional Jindalee background noise level for the same time interval is also plotted for comparison with the spectral surveillance data. The difference between this background noise and the noise inferred from the spectral surveillance data is typically in the range 3-5 dB at times when spectral usage is high, particularly at dusk and at low frequencies as the migration of HF spectral users to low frequencies boosts the recorded spectral surveillance power. Extreme discrepancies of up to 13 dB have also been observed. It may also be argued that the rapid temporal variation of the Jindalee background noise measurements is inconsistent with the physically anticipated background noise, which should be a smooth function of both frequency and time.

Given the evident problems with the Jindalee background noise estimates, the spectral surveillance data was used here to directly infer background noise for each statistically similar HF channel of width $2N_c$ kHz. Estimates were made on a channel-by-channel basis. For narrow channels less than 1 MHz wide, all 2 kHz spectral surveillance channels in a 1 MHz band (centred on the particular channel to be modelled) were rank ordered, and the background noise estimate chosen as the minimum surveillance power, after excluding low power outliers in the data. For statistically similar channels broader than 1 MHz, background noise estimates were obtained using the same rank ordering procedure, except that estimates were obtained for each 1 MHz band in the broard surveillance channel.

4 Jindalee Data Analysis

The Jindalee spectral surveillance database was used to obtain relative frequency estimates for the three parameters describing the cyclostationary Markov model for channel availability outlined in Section 2. Rather than attempting the computationally expensive task of modelling every month in the database, five specific months of data were chosen as representatives of the range of seasonal and solar cycle variability, in order to focus on long term trends in spectral usage. The three chosen months spanning the extremes of propagation conditions were June 1986 (winter, low solar activity year), January 1991 (summer, high solar activity year) and September 1993 (mid-season, mid-solar cycle year). June 1985 and June 1995 were chosen as months with similar seasonal and solar cycle conditions to evaluate changes in spectral usage in the decade 1985-95.

The HF spectrum for each month was manually segmented into channels in which spectral usage was judged to be statistically similar after a visual inspection of the data. Although choosing the ITU frequency allocations to segment the HF spectrum may be the initially favoured procedure, observed patterns of spectral usage within and across the ITU allocations necessitated the manual segmentation. About fifty statistically similar channels spanning 5-30 MHz were identified for each month of data, with channels varying in width from 100 kHz to almost 5 MHz. Channel availability was defined as in (2) using a threshold $T = 7$ dB, so that a channel is considered occupied if the spectral surveillance power is at least 7 dB above the background noise level estimated using the procedure described in Section 3. As an example, the subtraction of the estimated background noise from the surveillance data displayed in Figure 1 is shown in Figure 5, and the binary channel availability data is shown for the same data in Figure 6, after imposing the 7 dB threshold.

Relative frequency estimates $\widehat{p}(h)$, $\widehat{\lambda}(h)$ and $\widehat{\mu}(h)$ for the model parameters were respectively obtained using (9), (10) and (11), for each hour $h = 0, 1, \ldots, 23$ and for each statistically similar HF channel. The model parameters estimated for September 1993 are respectively displayed as spectrograms in Figures 7(a), 7(b) and 7(c).

Not surprisingly, the spectrogram morphology for $\widehat{p}$ (Figure 7(a)), the unconditional probability estimate of channel availability, resembles the temporal and frequency structure of the spectral surveillance data (e.g., Figure 1). In particular, clear channels are unlikely at low frequencies at night, and in strong broadcast bands (e.g., near 9.8 MHz, 11.8 MHz, 15.3 MHz and 17.8 MHz). The spectrograms for $\widehat{\lambda}$ (Figure 7(b)) and $\widehat{\mu}$ (Figure 7(c)) exhibit similar structure, but require more careful interpretation. The model parameter λ, the probability of channel availability given the availability at the preceding sample time, gives a measure of the temporal behaviour of spectral users. While $\widehat{p}$ estimates show that low frequency night time channels are not often available in September 1993, the $\widehat{\lambda}$ estimates for the same spectrogram region show that persistent spectral users are confined to relatively narrow bands within 5-10 MHz, and that channels with short-term availability can usually be found. A similar pattern is manifested in the $\widehat{\mu}$ estimates, implying that broadband spectral occupancy is strongly correlated with persistent usage.

Model parameter estimates for the extremes of seasonal and solar cycle HF propagation conditions are shown in Figures 8(a)-8(c) (June 1986) and Figures 9(a)-9(c); parameter

estimates for the mid-season, mid-cycle month of September 1993 (Figures 7(a)-7(c)) naturally fall between these extremes. Comparing Figure 8(a) with Figure 9(a) for the $\widehat{p}$ parameter estimates, it is evident that spectral availability at low frequencies and at night decreases with improving propagation conditions, as users make greater use of the HF environment. Conversely, daytime low frequency channels (less than about 15 MHz) show increased apparent availability as increased ionospheric absorption takes effect. High frequency channels (greater than about 15 MHz), particularly near the 21.5 MHz broadcast band and the 27 MHz CB bands, show greater occupancy throughout the day with improved HF propagation conditions. Similar trends are manifest by the $\widehat{\lambda}$ estimates (Figures 8(b) and 9(b)) and the $\widehat{\mu}$ estimates (Figures 8(c) and 9(c)).

Long term trends in spectral usage may be assessed by comparing the Markov model estimates obtained from spectral surveillance data sets recorded at widely separated times with similar propagation conditions. Parameter estimates for June 1985 and June 1995 are displayed in Figures 10 and 11 respectively, both being winter months in years of low solar activity, but in successive solar cycles. Most noteworthy in the comparison of these estimates is the increased channel availability over the decade, particularly at night time at low frequencies when clear channels are at a premium, e.g., comparing Figures 10(a) and 11(a). This decreased HF spectral usage reflects the trend away from voice to digital HF transmission, and to increased use of satellite and cable for long-distance communication. Comparing the $\widehat{\lambda}$ estimates in Figures 10(b) and 11(b), it may also be inferred that spectral users are occupying available channels for shorter periods, again explained by the increased prevalence of digital coded transmission. In contrast, the bandwidth requirements of users have remained relatively stable, as shown by the similarity of the $\widehat{\mu}$ estimates displayed in Figures 10(c) and 11(c).

5 Discussion

In this report, a two-dimensional cyclostationary Markov model for HF channel availability has been presented which generalises the spectral occupancy model of Gibson and Arnett [11, 12] to account for diurnal periodicity in the observed data. The three model parameters have been estimated for all frequency channels in the range 5-30 MHz using Jindalee spectral surveillance data recorded in Central Australia for five representative months in the last decade. This three parameter model is the minimum model which permits estimates of channel availability as a function of both bandwidth and duration, for all times of the day. With the extensive Jindalee spectral surveillance database, an assessment of long term trends in spectral usage can be made.

Using the model presented here, several quantities relevant to HF radar and communications operations can be derived. The expressions given by Gibson [9] for the expectation and variance of the number of clear channels and the probability of a clear channel with a given bandwidth, can be generalised to the cyclostationary model outlined here using a straightforward change in notation. The standard theory of Markov processes detailed in the references cited in Section 1 can be applied to derive further HF system design quantities of interest.

Thorough testing of the validity of the Markov channel availability model has yet to be completed. Preliminary test results have have been encouraging in justifiying the assumptions implicit in the model. For example, the first order approximation $\Lambda^{(1)}$ given by (17) for the two-dimensional conditional probability (16) is diplayed in Figure 12(a) for comparison with the direct estimate $\widehat{\Lambda}$ derived from the surveillance data using (19) and shown in Figure 12(b). The comparison suggests that the first order approximation holds for all frequency channels and times of day, with only a slight underestimation error for some low frequency channels at night. Some statistical testing of the model assumptions is also desirable. Gibson [9] has outlined several χ^2-tests which may be applied to the model assumptions, although many require the computation of second order transition probability estimates which are beyond the scope of this analysis. However, χ^2-testing on the hypothesis that the three model parameters for a given hour were stationary over a month was performed for sample frequency channels. For the five representative months analysed, the hypothesis was supported by the χ^2 statistic to a high degreee of confidence, justifying the underlying model assumption of diurnal cyclostationarity.

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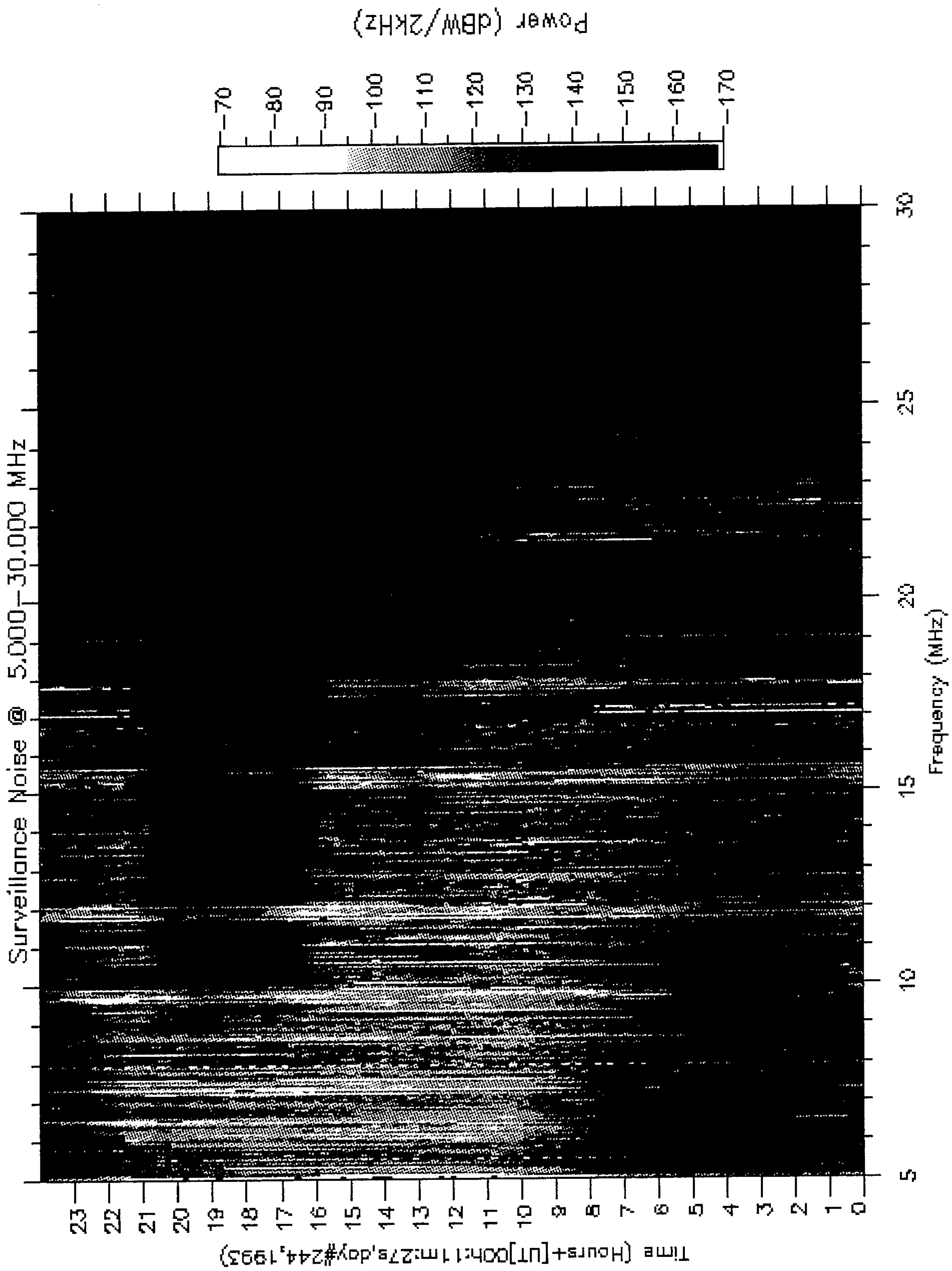

Figure 1: Jindalee spectral surveillance data for Day 244, September 1993, displayed as an intensity spectrogram in units of dB/2kHz.

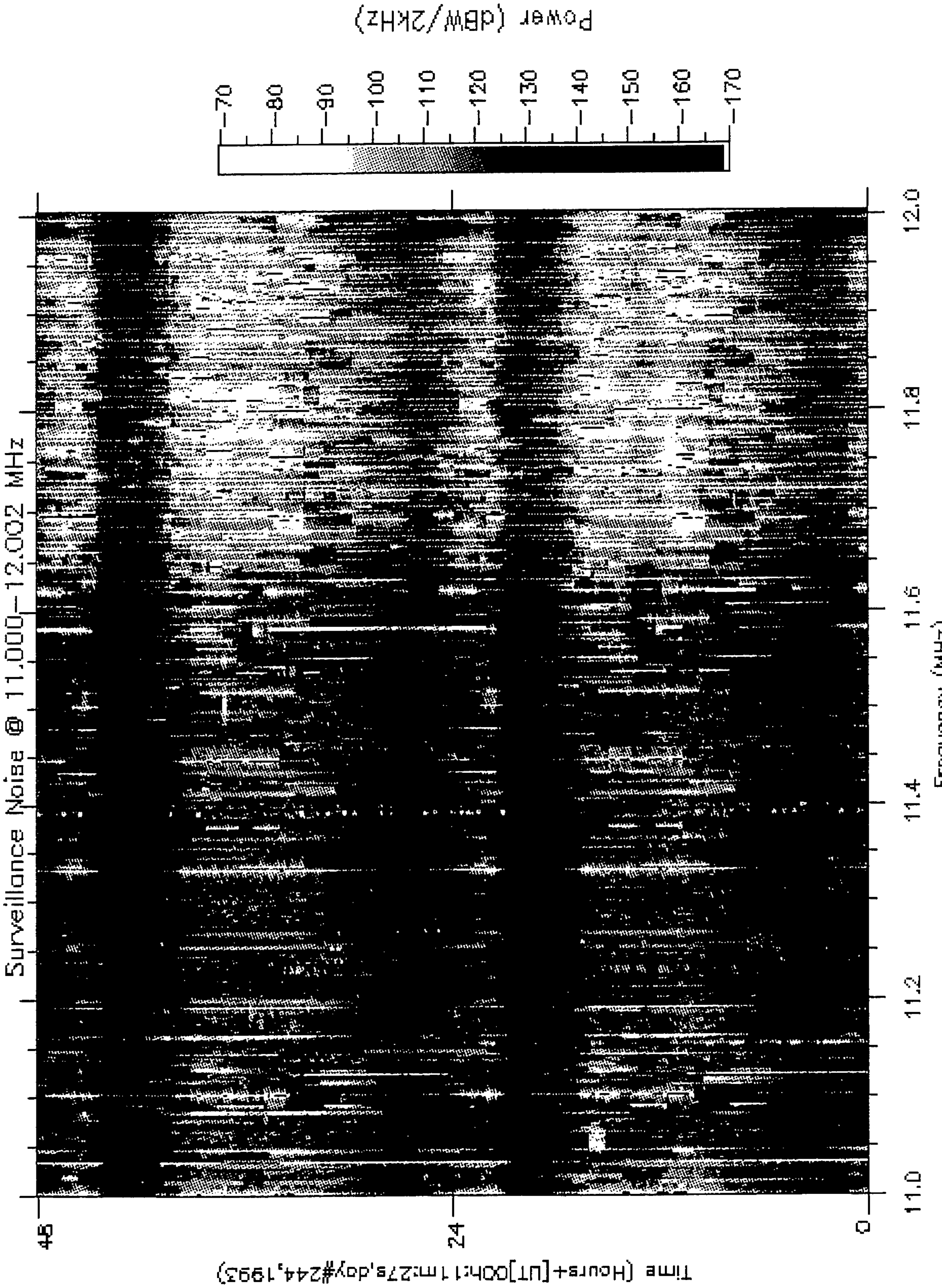

Figure 2: Jindalee spectral surveillance data for Days 244-245, September 1993, recorded in the range 11-12 MHz, and displayed as an intensity spectrogram in units of dB/2kHz.

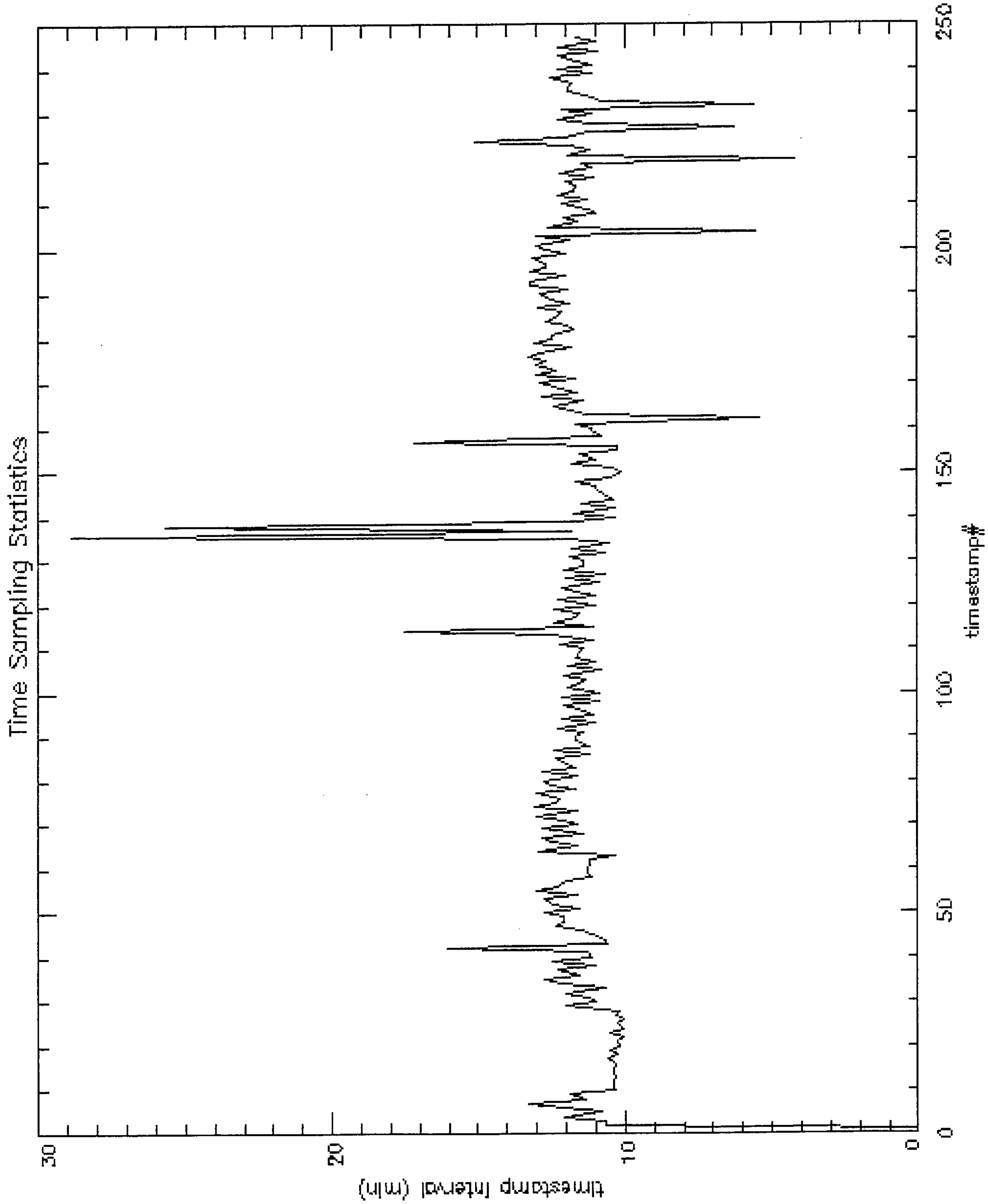

Figure 3: Graph of time interval between successive Jindalee surveillance records versus sample number. The average 12 minute sampling interval is manifested, together with occasional data gaps and data oversampling.

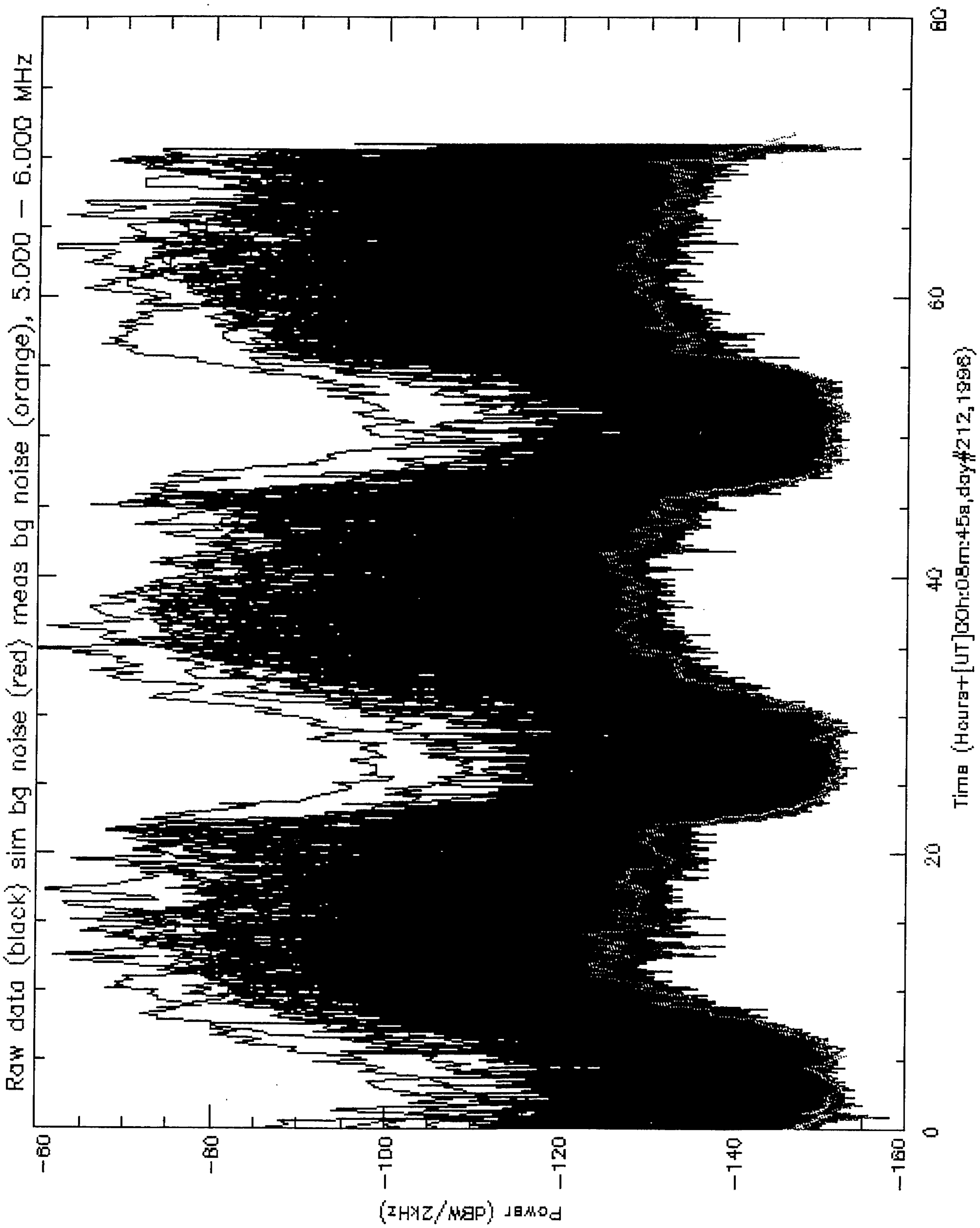

Figure 4: Comparison of Jindalee spectral surveillance data with background noise data. The power in five hundred 2 kHZ bandwidth channels in the range 5-6 MHz recorded over three days in July 1996 is plotted as superimposed black lines, forming a continuous plot region. The background noise level inferred from this data (excluding low power outliers) is shown (red line). The background noise level recorded by the Jindalee background noise subsystem (orange line) is biased by spectral usage.

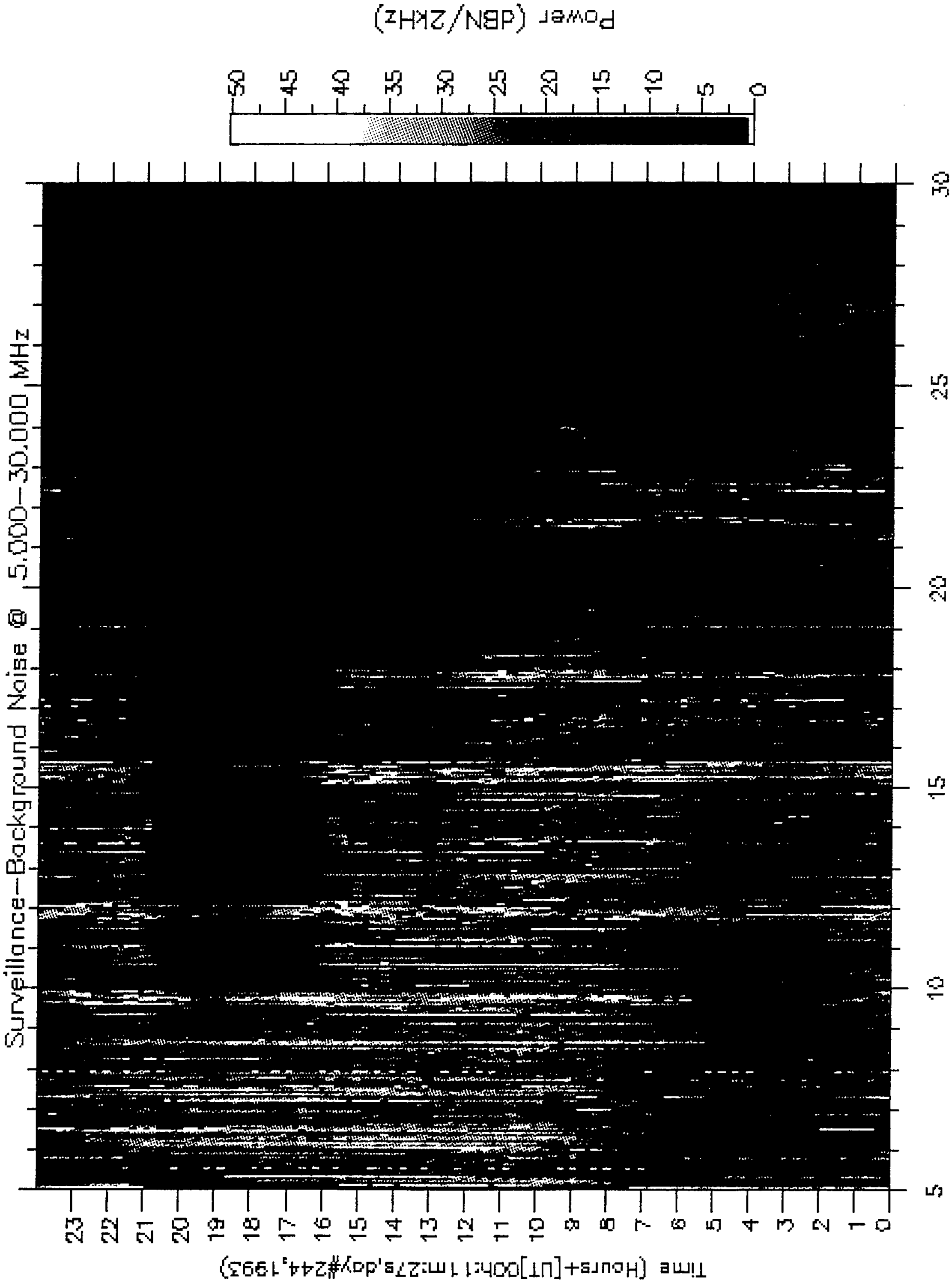

Figure 5: Jindalee spectral surveillance data above the estimated background noise for Day 244, September 1993.

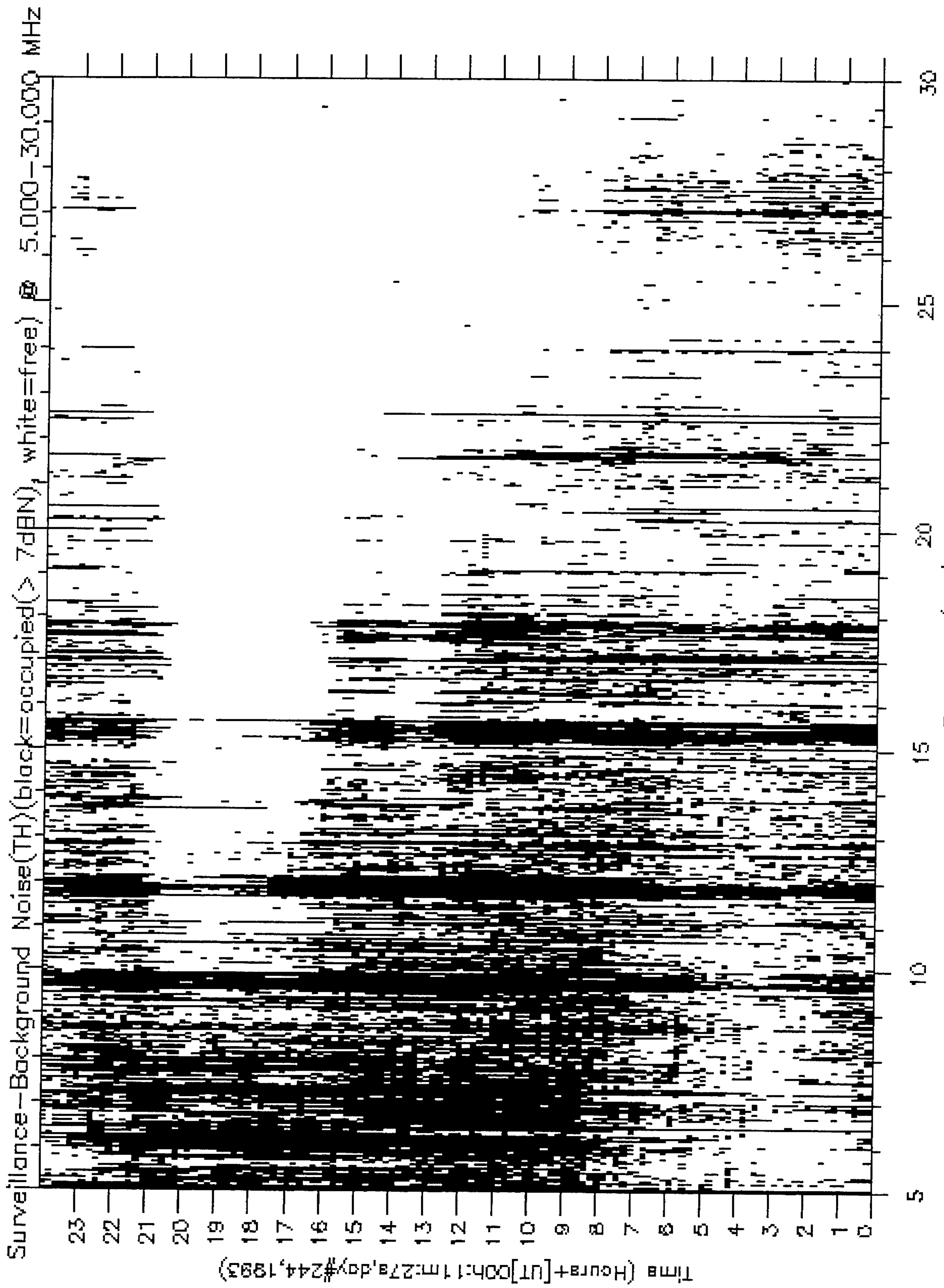

Figure 6: Channel availability function spectrogram derived from Jindalee spectral surveillance data for Day 244, September 1993. Black pixels denote occupied channels; complementary white pixels denote free or available channels.

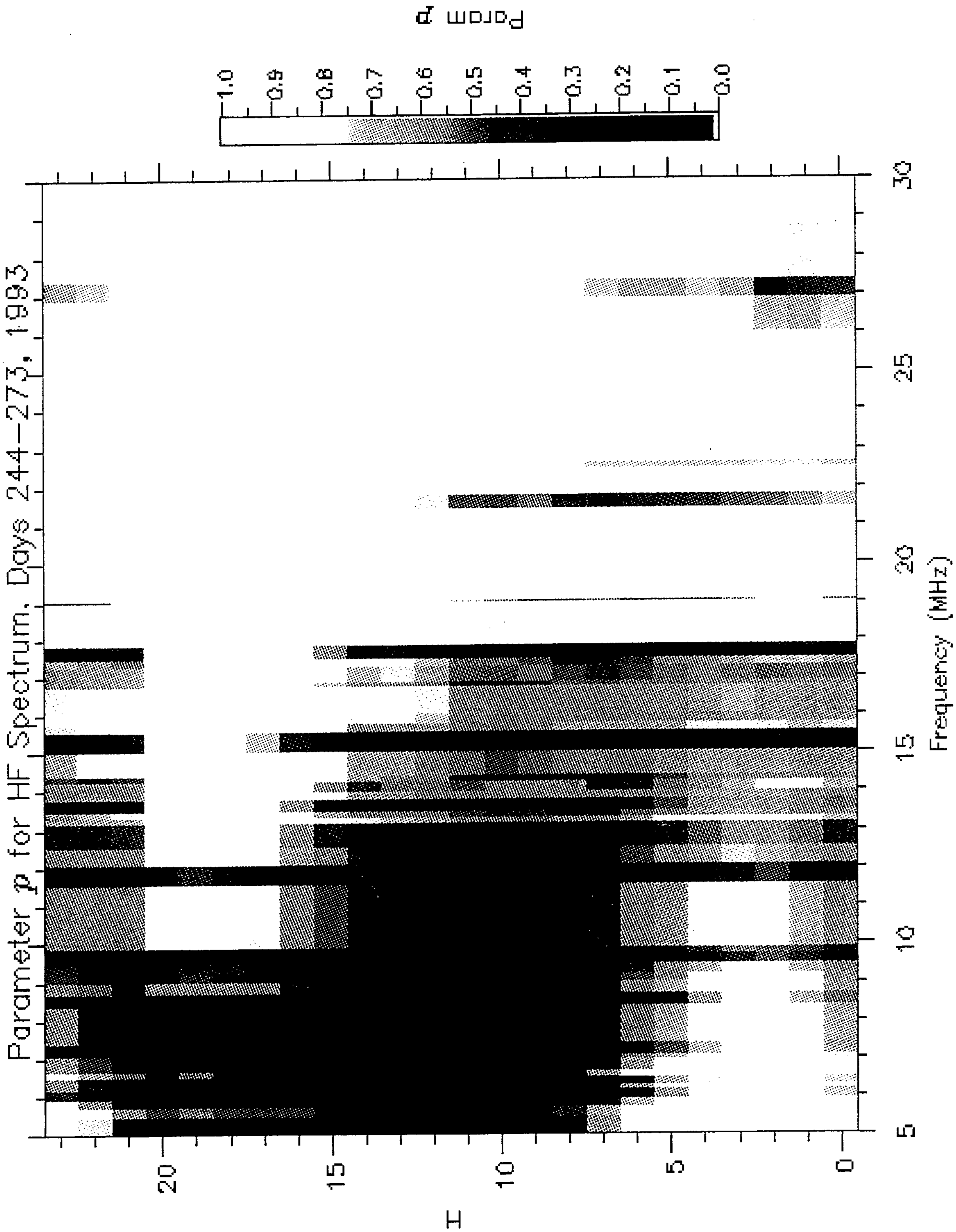

Figure 7 (a): Spectrogram of the relative frequency estimate $\widehat{p}$ for the unconditional probability of channel availability obtained using the Jindalee spectral surveillance data recorded in September 1993.

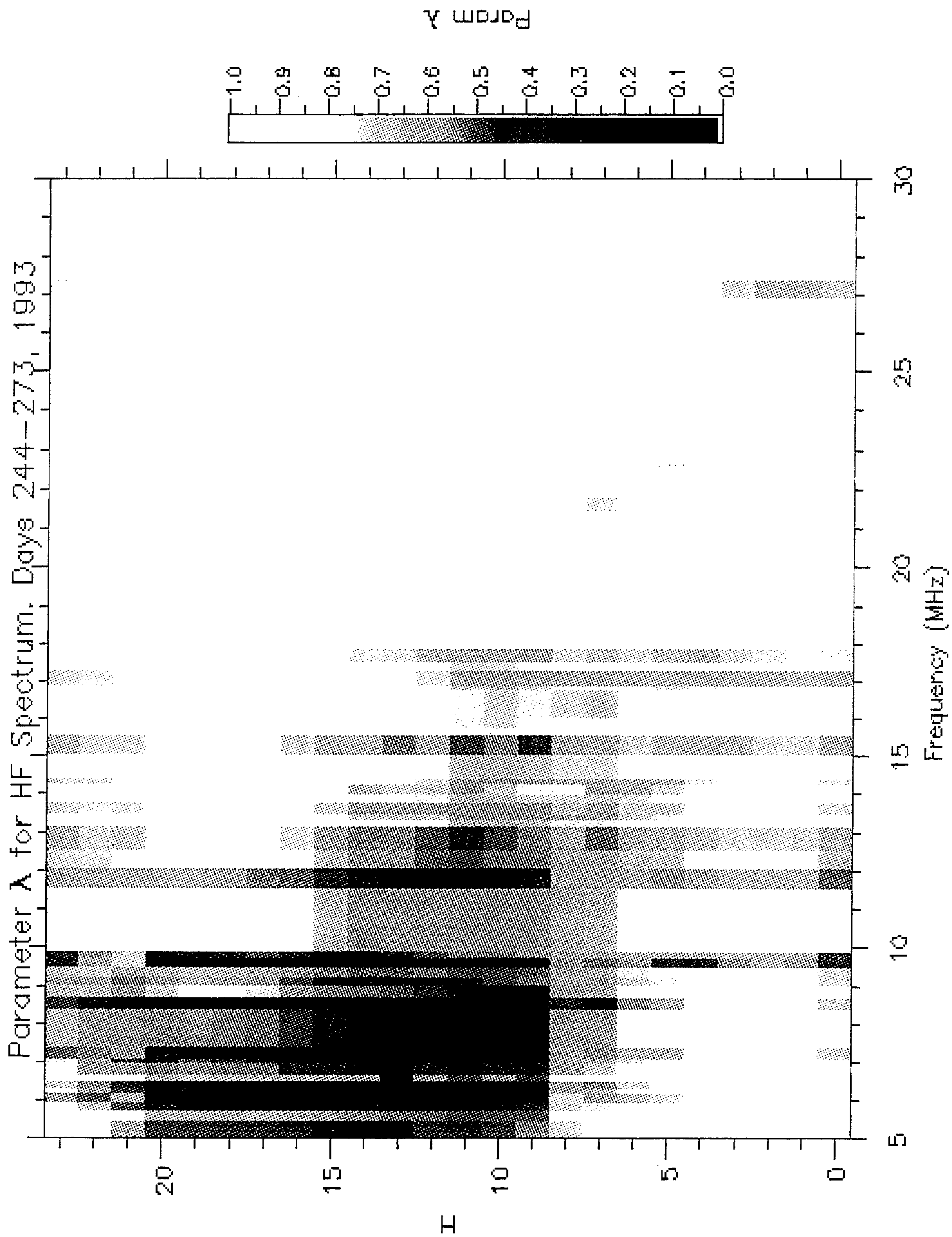

Figure 7 (b): Spectrogram of the relative frequency estimate $\widehat{\lambda}$ for the probability of channel availability conditional on channel availability in the previous time step obtained using the Jindalee spectral surveillance data recorded in September 1993.

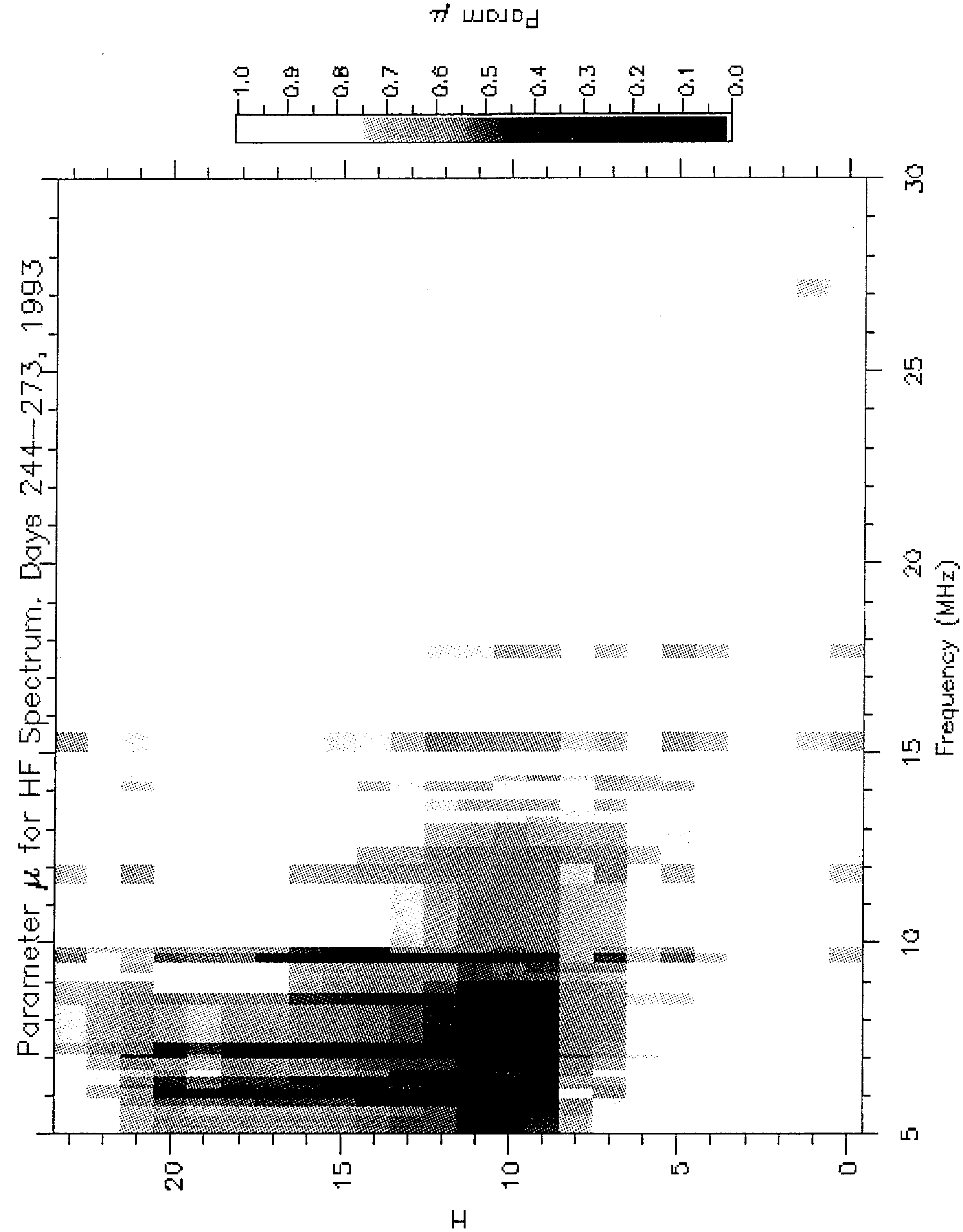

Figure 7 (c): Spectrogram of the relative frequency estimate $\widehat{\mu}$ for the probability of channel availability conditional on channel availability in the adjacent frequency channel obtained using the Jindalee spectral surveillance data recorded in September 1993.

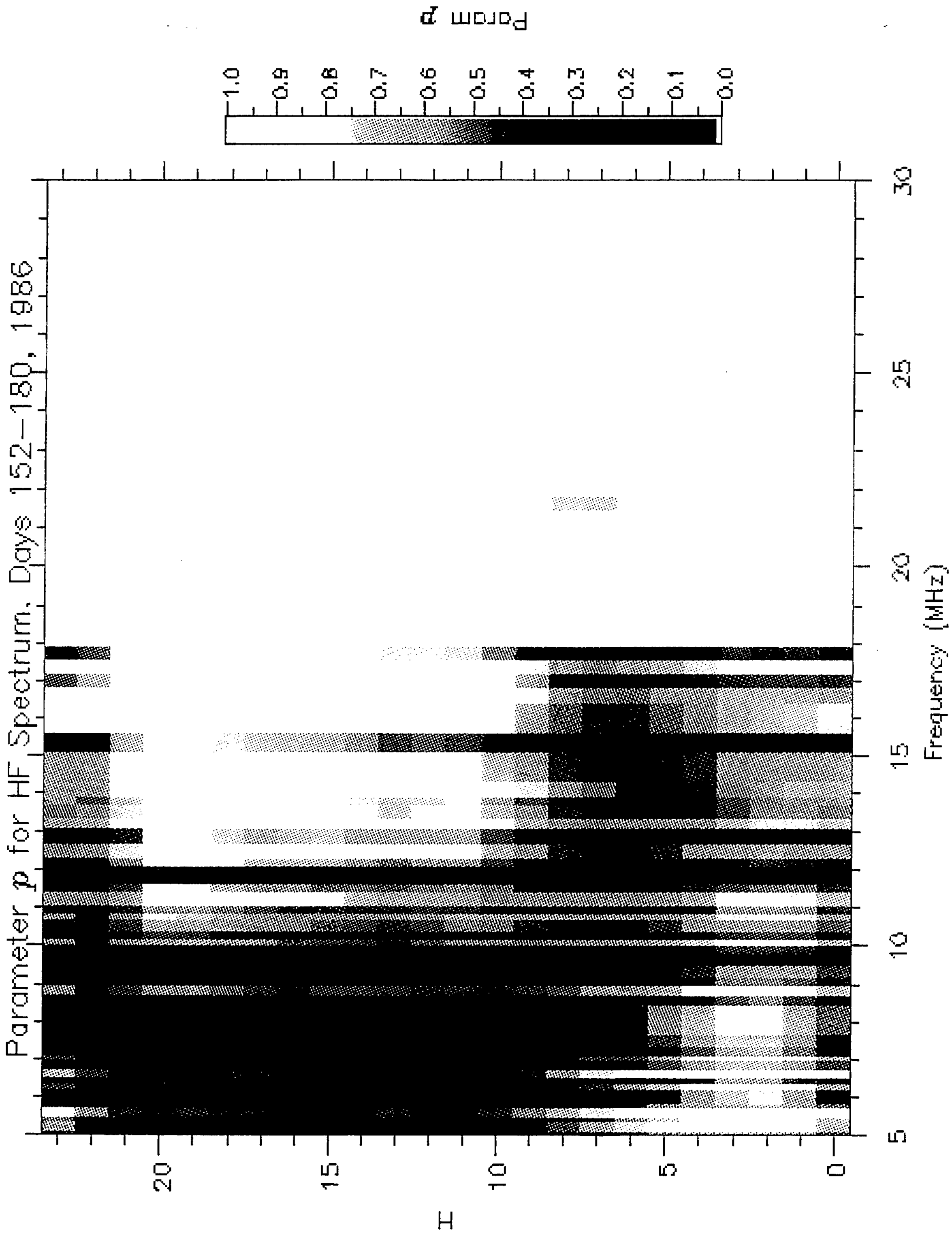

Figure 8 (a): Channel availability probability estimate $\widehat{p}$, for June 1986.

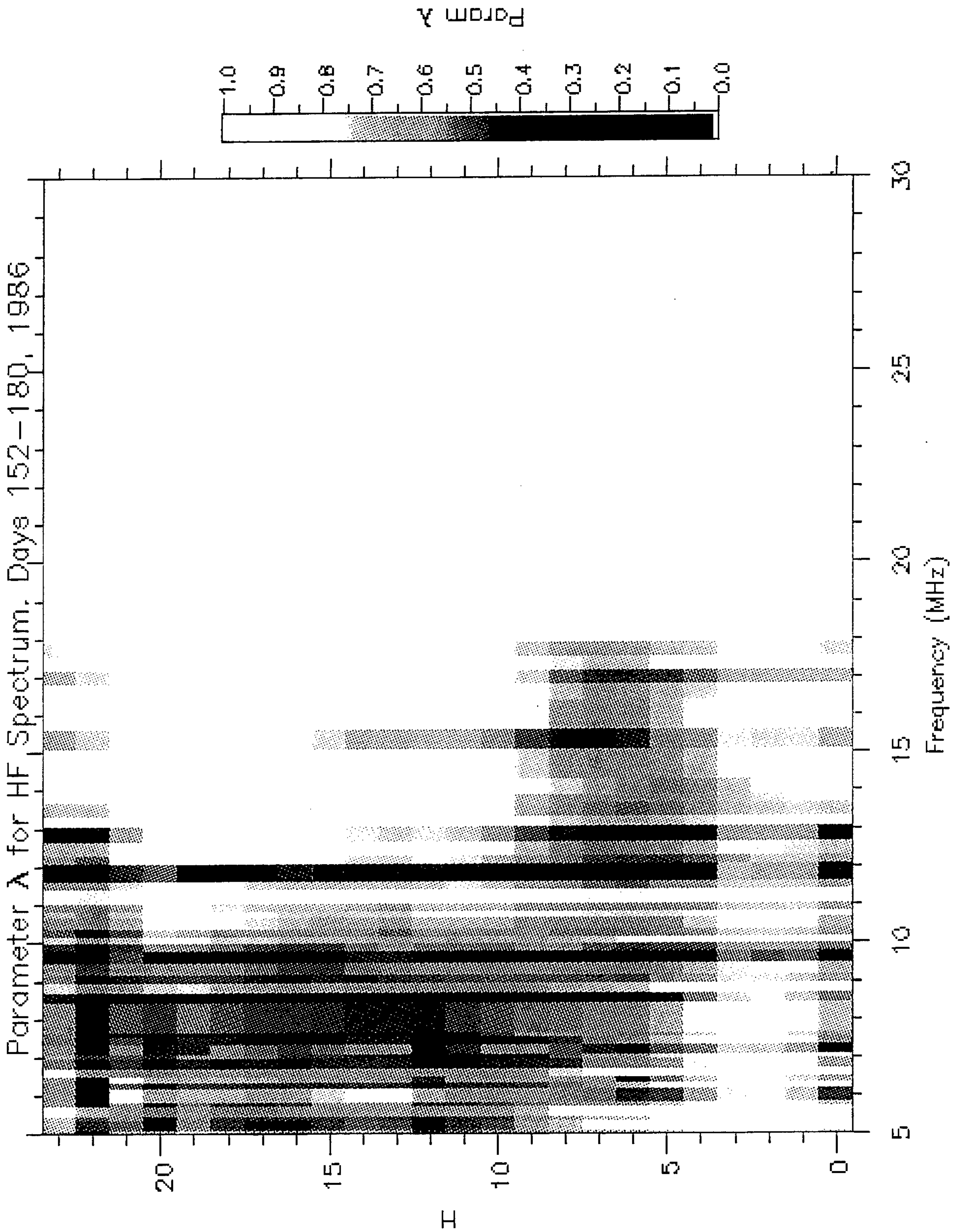

Figure 8 (b): Channel conditional transition probability estimate $\widehat{\lambda}$ for June 1986.

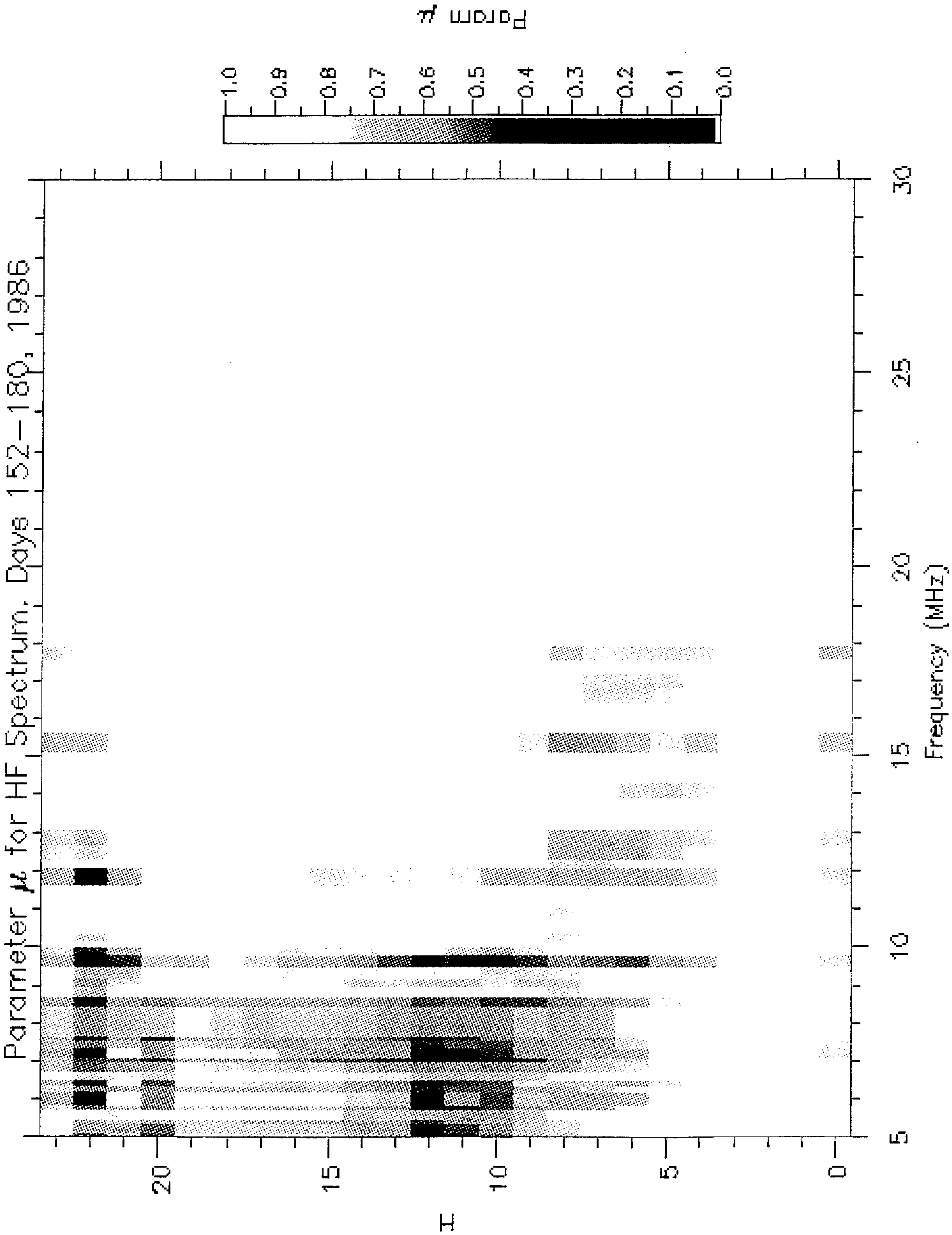

Figure 8 (c): Intra-channel conditional probability estimate $\widehat{\mu}$ for June 1986.

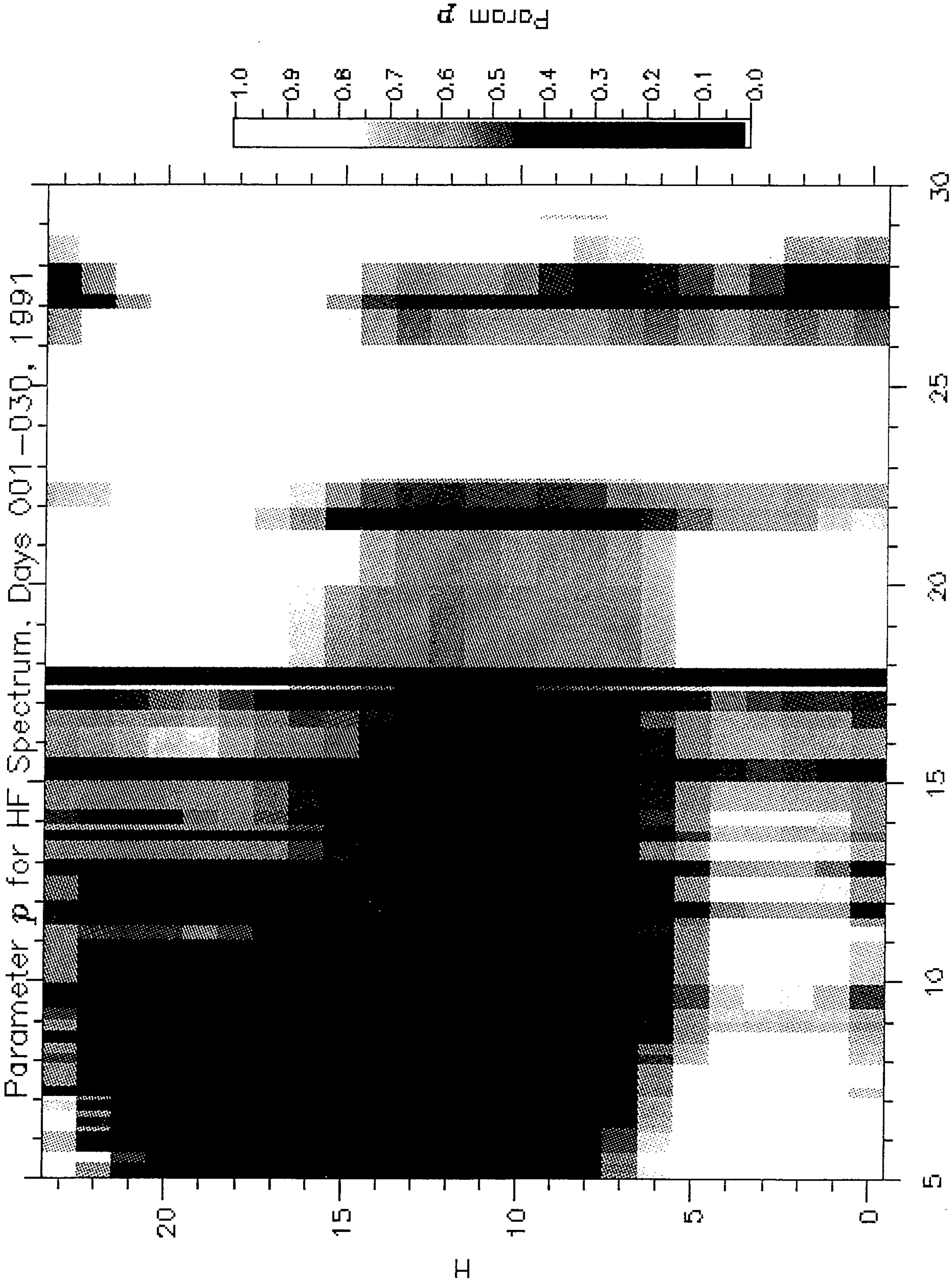

Figure 9 (a): Channel availability probability estimate $\widehat{p}$, for January 1991.

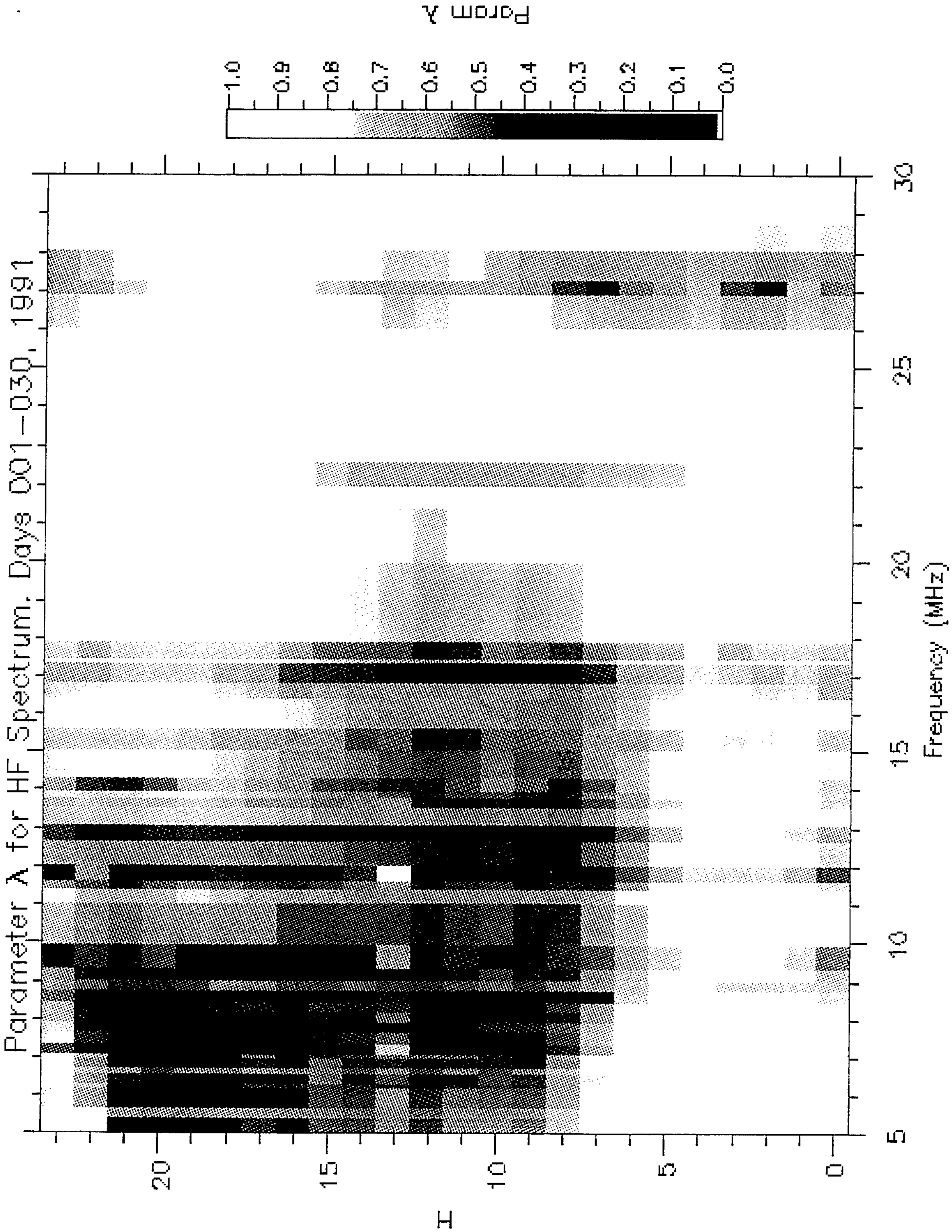

Figure 9 (b): Channel conditional transition probability estimate $\widehat{\lambda}$ for January 1991.

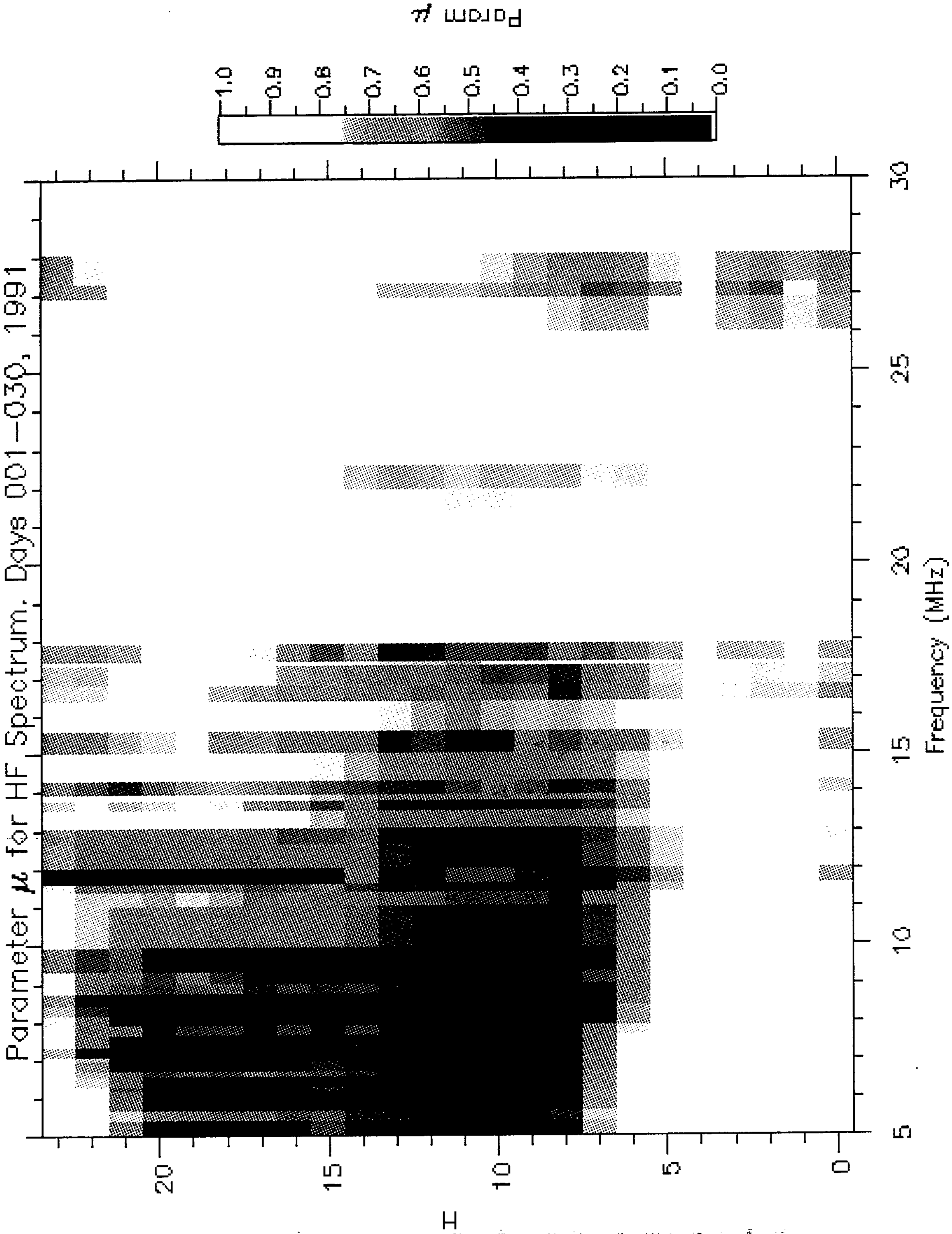

Figure 9 (c): Intra-channel conditional probability estimate $\widehat{\mu}$ for January 1991.

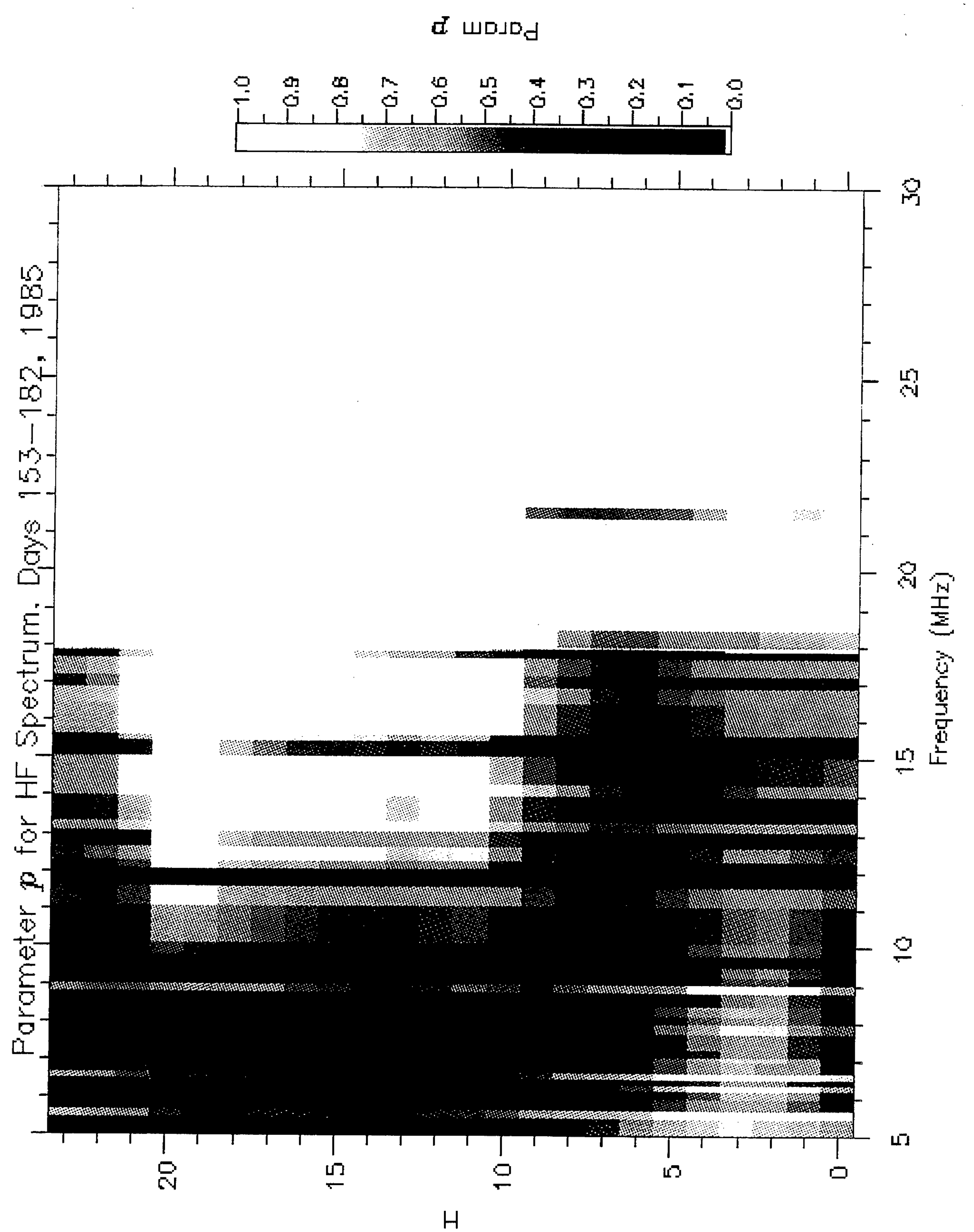

Figure 10 (a): Channel availability probability estimate $\widehat{p}$, for June 1985.

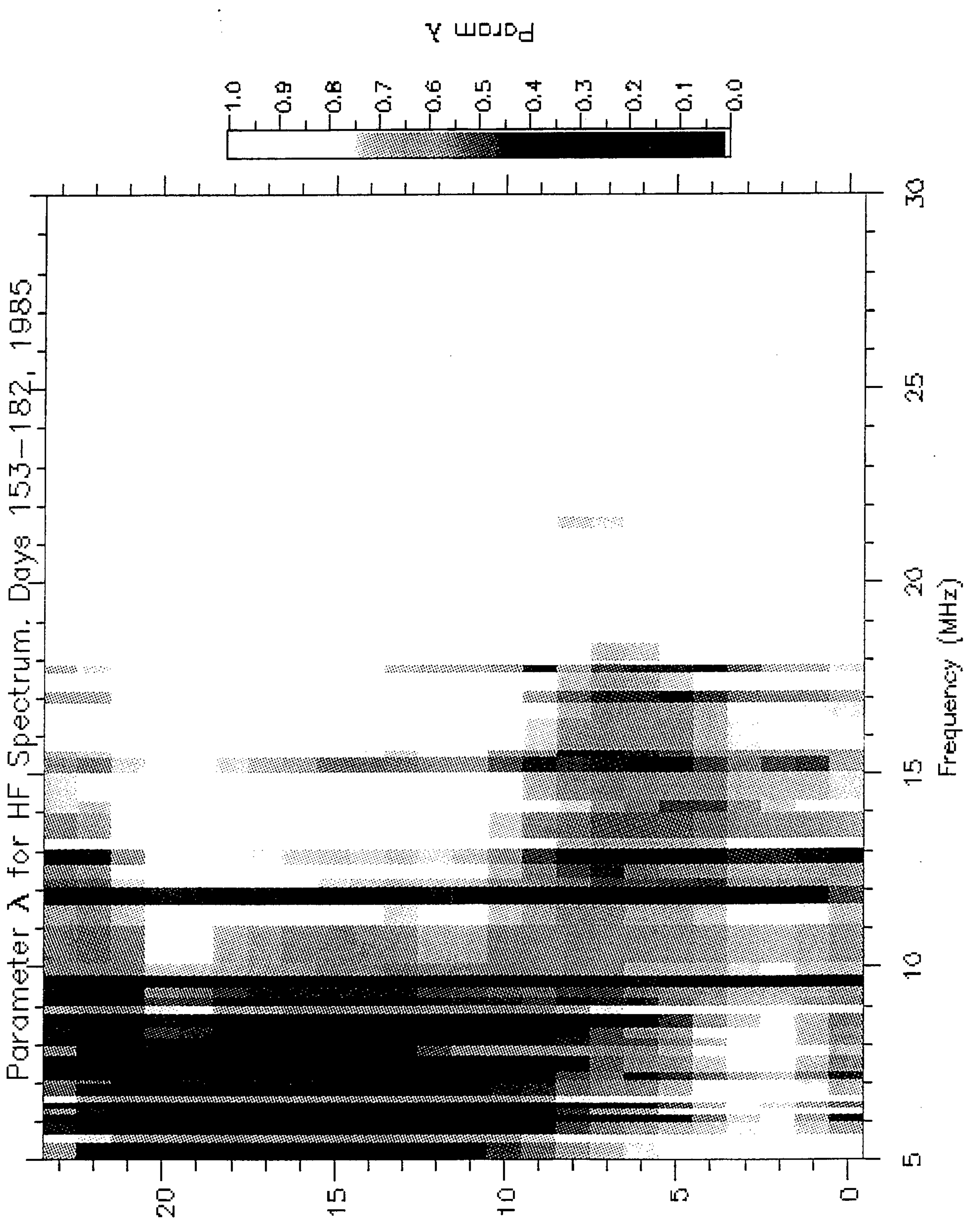

Figure 10 (b): Channel conditional transition probability estimate $\widehat{\lambda}$ for June 1985.

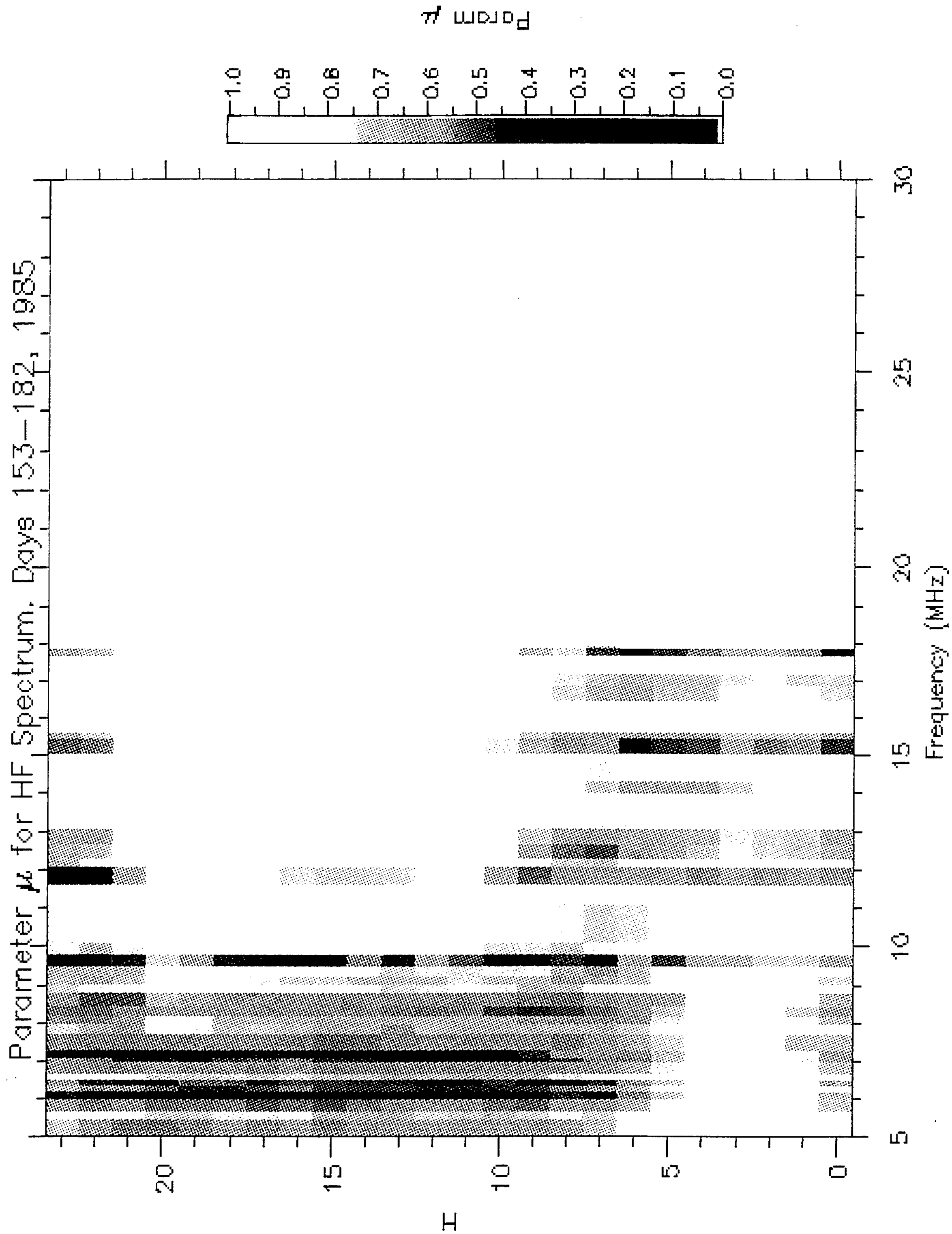

Figure 10 (c): Intra-channel conditional probability estimate $\widehat{\mu}$ for June 1985.

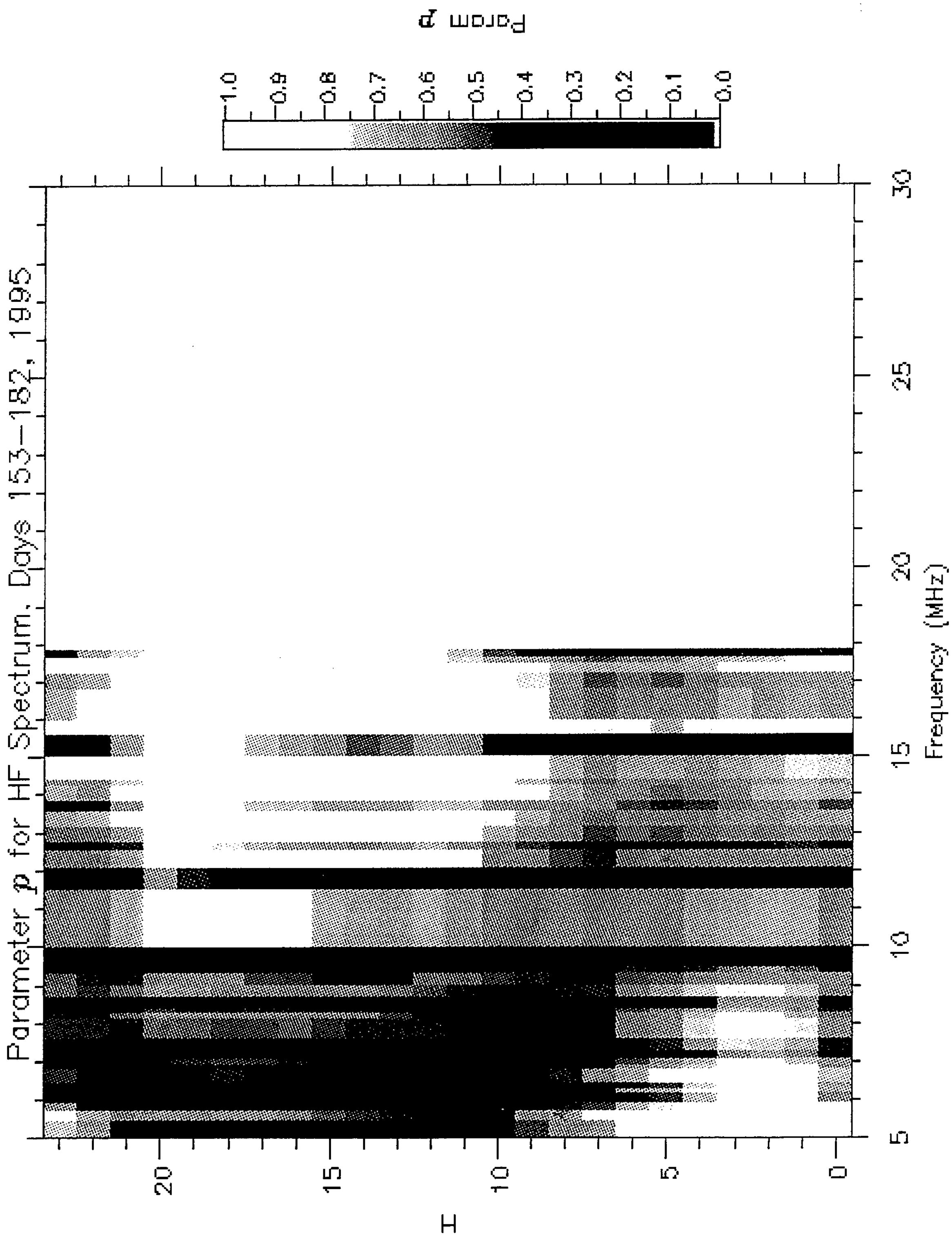

Figure 11 (a): Channel availability probability estimate $\widehat{p}$, for June 1995.

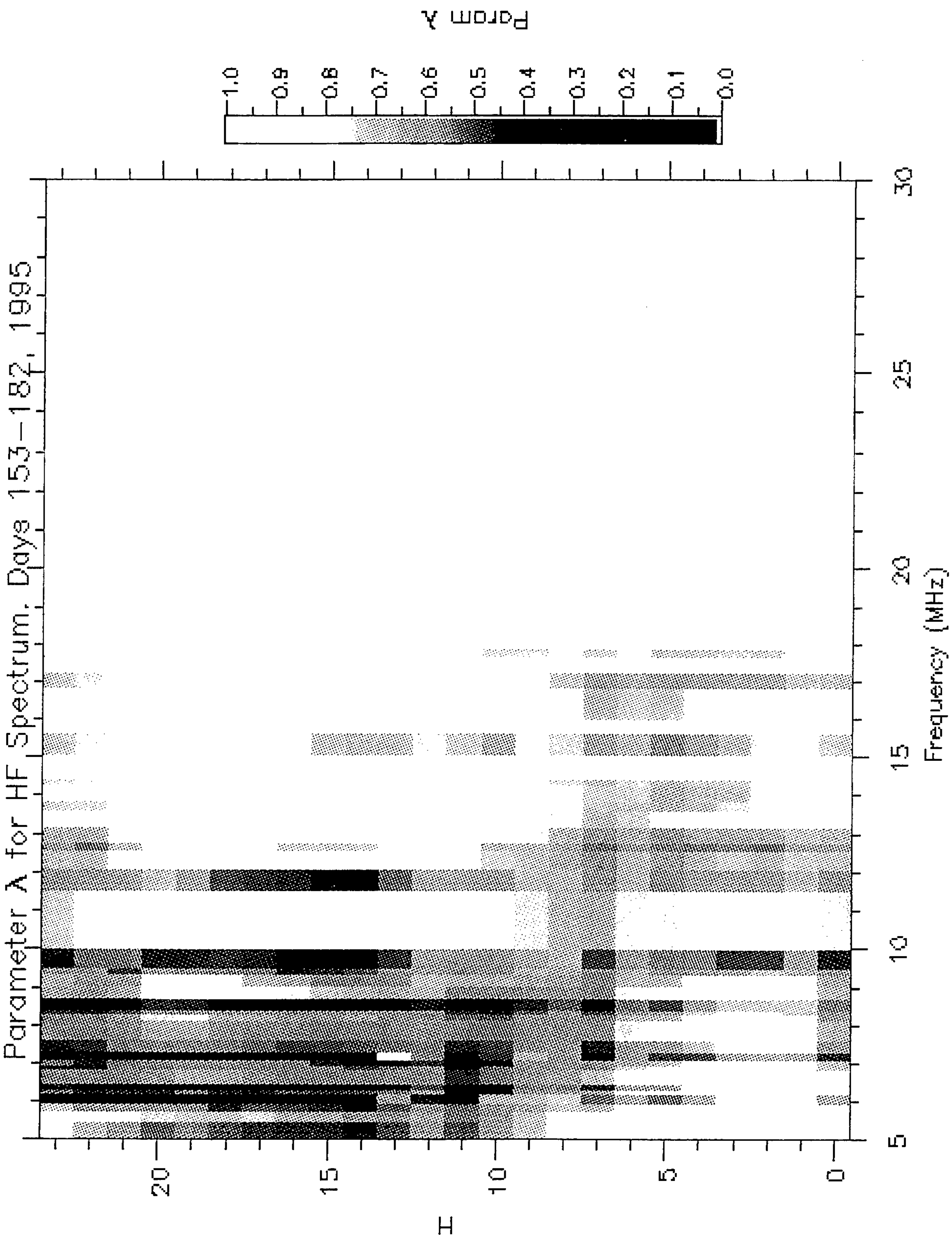

Figure 11 (b): Channel conditional transition probability estimate $\widehat{\lambda}$ for June 1995.

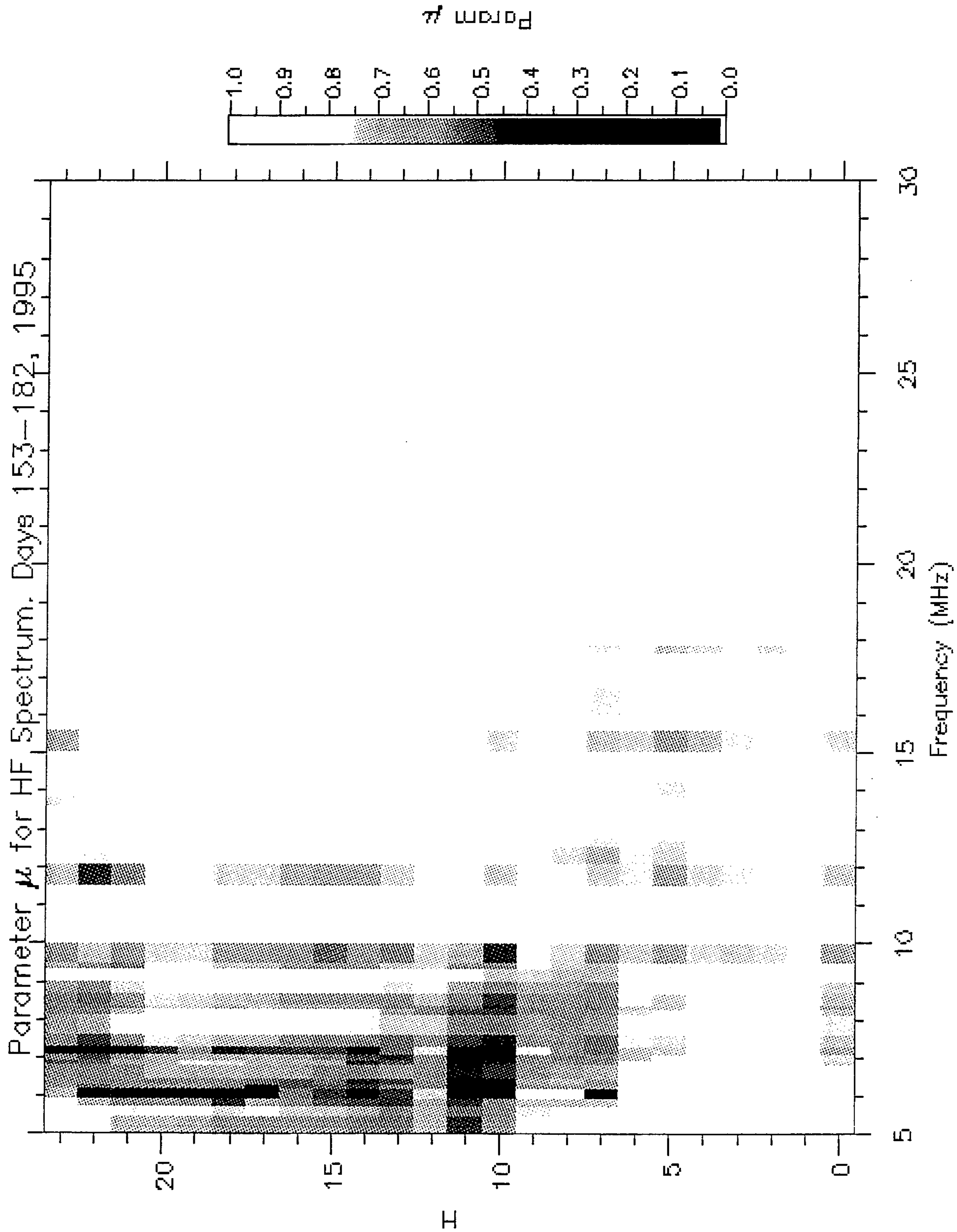

Figure 11 (c): Intra-channel conditional probability estimate $\widehat{\mu}$ for June 1995.

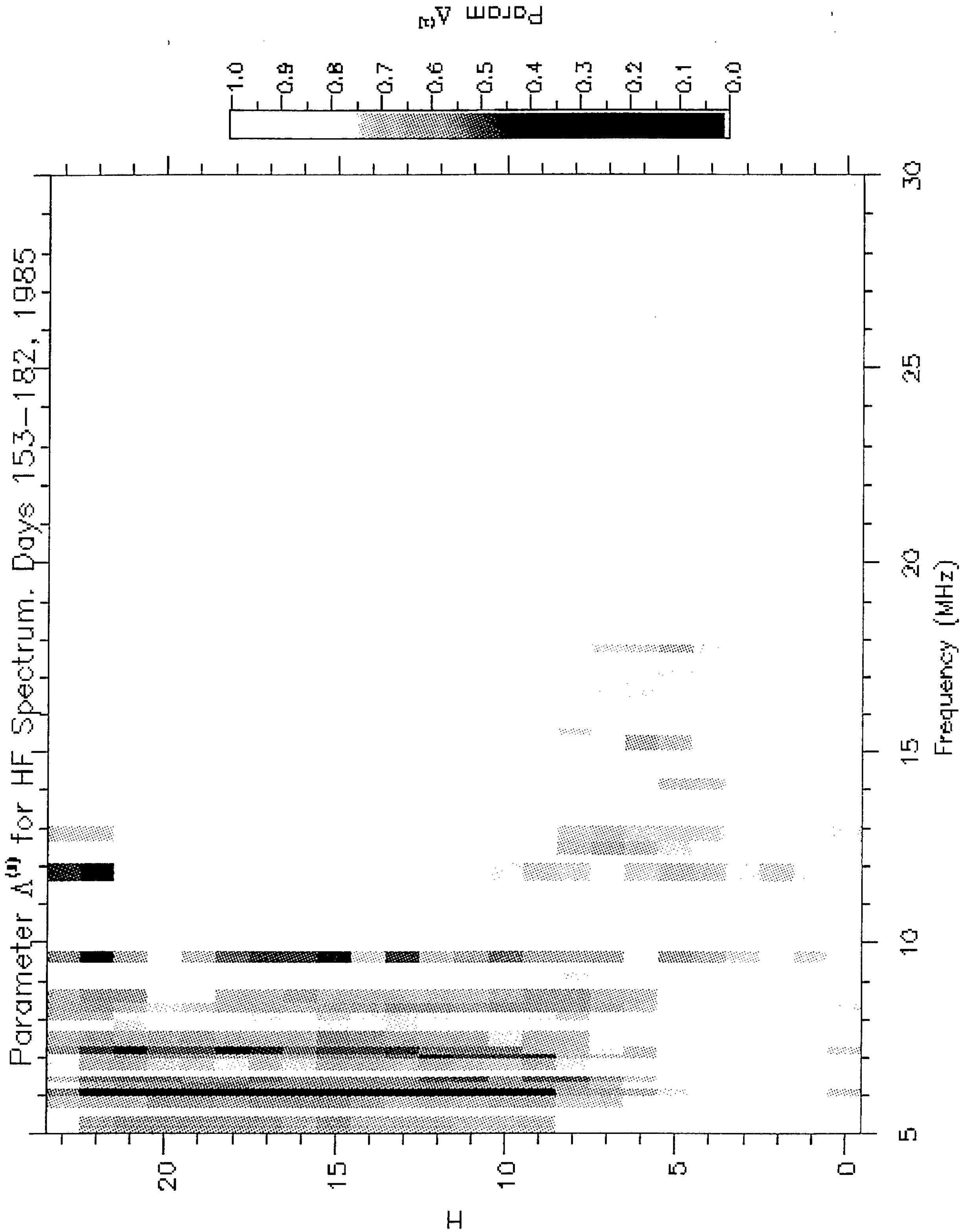

Figure 12 (a): First order approximation $\Lambda^{(1)}$ for the two-dimensional Markov model parameter estimate $\widehat{\Lambda}$, computed data for June 1985.

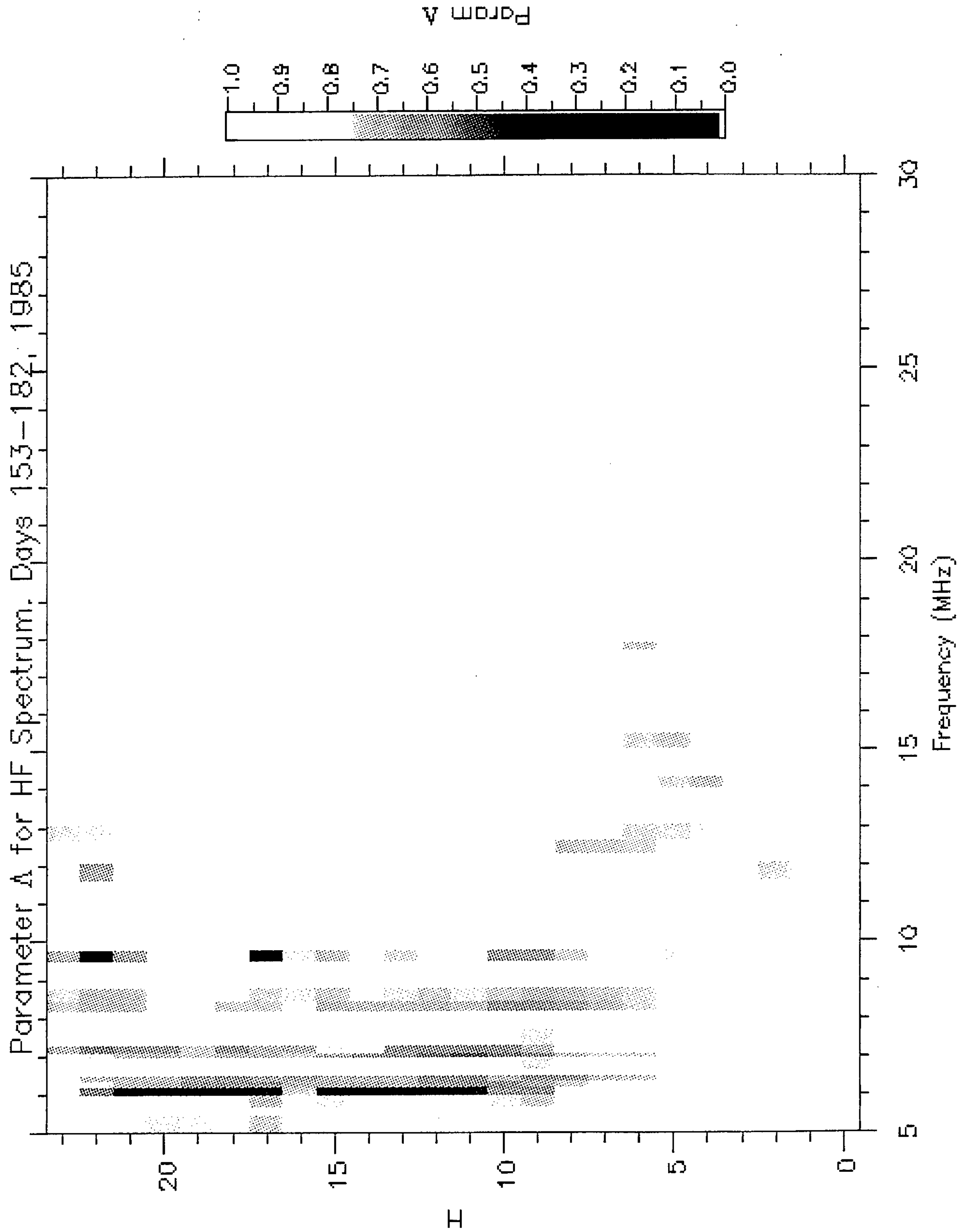

Figure 12 (b): Two-dimensional Markov model parameter estimate $\widehat{\Lambda}$ for June 1985.

Appendix A

Gibson and Arnett [11] introduced the first-order two-dimensional model for spectral occupancy, which includes within-channel and between-channel transition probabilities with the unconditional probability of channel availability which is modelled in the work of Laycock and Gott. We want to solve a system of eight linear equations in variables Φ_{klm} which were introduced in (15).

Spaulding and Hagn [24] suggested the usage of a first-order Markov chain for modelling the spectral occupancy of a single channel evolving in time. Following [17], it is easy to prove that from (5) and (6), using

$$q(h) = \Pr[x_j(d, h', t_i) = 0 | h' = h] = 1 - p(h) \tag{A1}$$

and the one-dimensional equivalent of (15)

$$\Phi_{kl}(h) = \Pr[x_j(d, h', t_i) = k | x_{j-1}(d, h', t_i) = l, h' = h], \;\; k, l = 0, 1 \tag{A2}$$

one obtains

$$q(h) = q(h)\Phi_{00} + p(h)\Phi_{01} \tag{A3}$$

and

$$p(h) = q(h)\Phi_{10} + p(h)\Phi_{11} \tag{A4}$$

as steady-state equations of the Markov process.

The corresponding two-dimensional steady-state equations are

$$q(h) = (q(h))^2\Phi_{000} + p(h)q(h)\Phi_{010} + p(h)q(h)\Phi_{001} + (p(h))^2\Phi_{011} \tag{A5}$$

and

$$p(h) = (q(h))^2\Phi_{100} + p(h)q(h)\Phi_{110} + p(h)q(h)\Phi_{101} + (p(h))^2\Phi_{111} \tag{A6}$$

Restricting the summation to one dimension at a time one obtains:

$$\Phi_{kl} = q(h)\Phi_{kl0} + p(h)\Phi_{kl1}, \;\; k, l = 0, 1 \tag{A7}$$

and

$$\Psi_{km} = q(h)\Phi_{k0m} + p(h)\Phi_{klm}, \;\; k, m = 0, 1 \tag{A8}$$

where Ψ_{km} is the frequency domain equivalent of Φ from (A2). Note that some equations in (A7) and (A8) are dependent.

We also have

$$\Phi_{0lm} + \Phi_{1lm} = 1, \;\; l, m = 0, 1 \tag{A9}$$

what is the consequence of the fact that the sum of the different (unconditional) probabilities of the final states must be equal to 1.

Because $\Phi_{0lm} = 1 - \Phi_{1lm}$, we reduce the 8×8 system (equations (A3) to (A8)) to an 8×4 system consisting of the equation (A5) (which is the same as (A6)) and

$$\Phi_{10} = q(h)\Phi_{100} + p(h)\Phi_{101} \tag{A10}$$

and

$$\Phi_{11} = q(h)\Phi_{110} + p(h)\Phi_{111} \tag{A11}$$

These equations were obtained from (A7). Similarly, from (A8) one has

$$\Psi_{10} = q(h)\Phi_{100} + p(h)\Phi_{110} \tag{A12}$$

and

$$\Psi_{11} = q(h)\Phi_{101} + p(h)\Phi_{111} \tag{A13}$$

It can be easily seen that equations (A10) to (A13) are dependent. As a consequence one has to introduce the conditional probability Λ as in (16).

From (A13) one has

$$\Phi_{101} = \frac{\mu(h) - p(h)\Lambda(h)}{1 - p(h)} \tag{A14}$$

and from (A11),

$$\Phi_{110} = \frac{\lambda(h) - p(h)\Lambda(h)}{1 - p(h)} \tag{A15}$$

From (A10) (or (A12)) we have

$$\Phi_{100} = \frac{p(h)\ (1 + p(h)\Lambda(h) - \lambda(h) - \mu(h))}{(1 - p(h))^2} \tag{A16}$$

(A9) yields the following expressions

$$\Phi_{011} = 1 - \Lambda(h) \tag{A17}$$

$$\Phi_{001} = \frac{1 - p(h) - \mu(h) - p(h)\Lambda(h)}{1 - p(h)} \tag{A18}$$

$$\Phi_{010} = \frac{1 - p(h) - \lambda(h) - p(h)\Lambda(h)}{1 - p(h)} \tag{A19}$$

and

$$\Phi_{000} = \frac{1 - p(h)\ (3 - \lambda(h) - \mu(h)) + (p(h))^2\ (1 + \Lambda(h))}{(1 - p(h))^2} \tag{A20}$$

In that way all two-dimensional transition probabilities Φ_{klm} are expressed in terms of Markov parameters $p(h), \lambda(h), \mu(h)$ and $\Lambda(h)$.

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D.J. Percival, M. Kraetzl and M.S. Britton

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4. AUTHOR(S) D.J. Percival, M. Kraetzl and M.S. Britton	5. CORPORATE AUTHOR Electronics and Surveillance Research Laboratory PO Box 1500 Salisbury SA 5108

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TR-0472	AR-010-124	Technical Report	February 1997

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
E8709/7/9	ADF93/319	DGFD(J)	41	28

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19. ABSTRACT

In this report, the extensive database of HF spectral surveillance and background noise measurements, recorded at Alice Springs in Central Australia as part of the Jindalee over-the-horizon radar project, is used to develop a model for HF channel availability. Parameters in a two-dimensional cyclostationary Markov model are estimated for representative months of Jindalee data. The resulting model may be used for short-term forecasting of HF channel availability for radar and communications, and as the starting point for a study into long-term trends in spectral usage.

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